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MACH: A model for explaining molecular and cellular mechanisms

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This dissertation is dedicated to my grandparents James Ferguson, Alice Scott Ferguson, Benjamin Trujillo, and Brigitte Trujillo.

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ABSTRACT

Trujillo, Caleb M. PhD, Purdue University, May 2015. MACH: A Model for Explaining Molecular and Cellular Mechanisms. Major Professors: Nancy J. Pelaez and Trevor R. Anderson.

Biologists use mechanistic explanations to understand behaviors of the immense complexity of molecular and cellular systems. In undergraduate biology courses, students are expected to explain molecular and cellular mechanisms, but teaching this skill presents many challenges due to the highly abstract, intangible nature of the cellular world, the influence of everyday language, and the tendency of students to overestimate how much they can explain. Therefore, across three studies this dissertation addresses these obstacles to teach undergraduate biology students to explain molecular and cellular mechanisms.

The first step was to model how biology experts explain molecular and cellular mechanisms, and to test the validity of this model by examining how experts from different biology sub-disciplines explain a mechanism they study. A literature review was performed to develop an initial model and then to determine the model's validity, it was tested against explanations made during interviews by life scientists who work on molecular and cellular mechanisms. The interview data were subjected to thematic analysis and four themes were found. Explanations of molecular and cellular mechanisms include: *Methods* (M) used in research to inform ideas about the mechanism, *Analogies* (A) such as representations, models, stories, and diagrams to illustrate the explanation, *Contexts* (C) to emphasize the social importance and biological setting of the mechanism, and *How* (H) the mechanism works to address the organization of biological entities and their activities. Biologists who are experts in their sub-disciplines integrated all four components to explain cellular and molecular

mechanisms. These themes formed the components of the MACH model, which extends previous models of molecular explanations and identifies components to include when teaching students how to explain biological mechanisms.

Then a teaching intervention using the MACH model was implemented in an introductory undergraduate biology course to find out: How does using the MACH model change the explanations written by life science students? Why do students think learning about the MACH model is useful, if at all? Student explanations collected before and after an intervention were subjected to content and statistical analysis. Student interviews were conducted and subjected to inductive analysis. Before the intervention, about 30% of responses included all MACH components; after the teaching intervention, the frequency rose to 90%. It was found that students used the model to monitor their understanding, to communicate completely and concisely, and to reveal gaps in their explanations. Results indicated a successful implementation of the model in the classroom, as well as, some unexpected problems. For instance, many students, unlike experts, struggled to integrate the MACH components in their explanations, and instead treated each component as a separate section.

Written for biology instructors, the third study presents knowledge and resources for using the MACH model in a classroom setting, and in doing so, furthers an understanding of how to make the components of explanation comprehensible to students. We discover pedagogical content knowledge (PCK) for teaching with the MACH model by asking: How does one help instructors and students understand and include the components biologists use to explain molecular and cellular mechanisms? Along with PCK, we present teaching resources including a tetrahedral model, a teaching activity, and a rubric for evaluating how well students use the MACH components when explaining molecular and cellular mechanisms.

As for the result of the three studies, a new framework for researching, teaching, and communicating molecular and cellular mechanisms has been developed. Future research will test the model against a large pool of explanations by scientists who study a variety of topics such as evolution or chemistry. Additionally, future stud-

ies will replicate the intervention presented, vary factors in more carefully controlled quasi-experimental studies, or study the development of explanatory skills without any intervention in naturalistic settings. Teachers may also develop new applications for teaching with the model across additional institutes, biological topics, student populations, and educational settings. The MACH model will further the scholarship of both research and teaching.

CHAPTER 1. INTRODUCTION

> There are no inanimate systems in the mesocosmos that are even anywhere near as complex as the biological systems of the macromolecules and cells.
>
> *Ernest Mayr*

I am frequently asked why I study and teach biological explanations, the topic of my dissertation. Typically, I respond by saying I am driven to help students explain because of the difficulties I faced when I was an undergraduate student learning explanations in biology. However, by writing this dissertation, I have reflected on the path that brought me to Purdue University. My inspiration took root at age fourteen when two major events occurred. The first event was enrollment in honors biology in which I instantly fell in love with the life sciences. The second, sobering event occurred when my father was diagnosed with Hairy Cell Leukemia.

While visiting my father in the the oncology wing of the hospital, I witnessed the doctor trying to explain to my father how chemotherapy was eradicating the leukemia. Despite my father's impassioned inquiry into how the drug was both poisoning and curing him, the oncologists was struggling to provide an answer without medical jargon that satisfied his curiosity. The doctor explained how the drug affected the immune cells' ability to replicate DNA, but my father was unfamiliar with this knowledge. Coincidentally, I had learned the replication mechanism that month in my biology course, so I interrupted to help the oncologist. My father was a cyclist, so I used the analogy of a jammed bicycle gear to connect the doctor's explanation to my father's understanding. As a freshmen in high school, I did not know the drug's action or the dozens of proteins involved in the mechanism, but in that hospital room,

I was able to help the oncologist communicate to her patient. Undoubtably, it was the first time I saw how an appropriate biological explanation affected someone on a personal and meaningful level. As I complete my dissertation, my father remains in remission, and now, I can appreciate how those two events brought me to study the explanations made by biologists and to teach biology students to explain.

This dissertation culminates my PhD study in the Biological Sciences at Purdue University. During my research, I have attempted to address three problems. The first problem is most familiar to biologists. The molecular and cellular living world has an inconceivable level of complexity and as such, explaining how the submicroscopic and microscopic world works is a challenge. The number of molecular mechanisms in a cell is intimidating to say the least, yet scientists work on these systems, develop an understanding of these interacting networks of molecules, and can explain their mechanism of interest to another scientist with relative ease when one considers the mess of interactions. That said, the first problem is to understand what do biologists include when explaining molecular and cellular mechanism. Once this problem is understood, a second problem arises. Undergraduate biology students are expected to develop skills related to biology, and this tradition of biology education depends on making these intricately complex systems comprehensible to learners, so the challenge, then, becomes how does one help students understand and use the components used by biologists to explain. In other words, how does one communicate the elements used by biologists to students who are learning about the invisible and highly abstract world of molecules and cells? Finally, provided one can resolve the issue to understand both what components biologists use to explain molecular and cellular mechanisms and what means are useful for teaching students these components, the next challenge is to communicate these successes to other biology educators. There is need to disseminate teaching resources and strategies that overcome these problems so that explanations of molecular and cellular mechanism may be better understood by students and instructors. To address these problems during my studies, I modeled the components that biologists include when they create explanations about molecu-

lar and cellular mechanisms, and then by implementing a teaching intervention with the produced model, I taught students the components used by biologists to explain such mechanism, and finally, I developed teaching resources and knowledge for explaining mechanisms in the classroom for other biology instructors. The dissertation reports my research in three manuscripts, which each address a problem. These are provided as chapters 2, 3, and 4. Each manuscript builds on a theory to address a purpose and research questions so that the data, analysis, and results contribute to the scholarship of biology and teaching. The purpose of this introductory chapter is to overview the subsequent chapters, while the fifth chapter ties the manuscripts into a larger report. Together, this work forwards an understanding of the role of explanations of molecular and cellular mechanisms in both biology and life science education.

1.1 Introduction to the first study and the MACH model

Chapter two features the first manuscript entitled, "A model of how different biology experts explain molecular and cellular mechanisms" (Trujillo, Anderson, & Pelaez, in press). The first manuscript models the components biologists include in their explanations of cellular and molecular mechanisms. Situated in the theory of mechanistic explanations, the first study is builds upon a model of molecular mechanisms to address what components biologists include when they explain. In principle, biologists who study cells and molecules hold a 'mechanistic' view of the world. This is because biological mechanisms focus on causes – an approach most appropriate for answering 'how' questions. As an operational definition used throughout this dissertation, *a biological mechanism describes how the component entities of a biological phenomenon interact at the molecular, microscopic, and macroscopic levels to produce detectable changes in state, activities, and spatial and temporal organization* (Machamer, Darden, & Craver, 2000; Trujillo et al., in press; van Mil, Boerwinkel, & Waarlo, 2013). The definition served as a starting point for understanding explana-

tions of molecular and cellular mechanisms. I ask: What is an appropriate model of the components of explanation used by biology experts when they explain molecular and cellular mechanisms? Do explanations made by experts from different biology sub-disciplines at a Midwestern U.S. research university support the validity of this model?

A model was developed using the model of modeling framework (Justi & Gilbert, 2002) and qualitative research methods to identify the essential aspects of biology experts' explanations of molecular and cellular mechanisms by identifying components found in their explanations. An initial model based on the literature served as a starting point, but the extent to which it captured the explanations of biologists was unknown, so exploratory interviews were conducted with practicing biologists to inform the modeling processes. In this way, empirical evidence could be gathered to test the initial model and to inform modifications.

A thematic analysis of these interviews revealed that, rather than creating strictly mechanistic explanation, the interviewed biologists who research molecular and cellular mechanisms included many other aspects in their explanations. The four themes from the explanations are represented by the letters of MACH. When explaining, biologists interweave:

- The *Methods* (M) of research used to gather information about the explanation;
- *Analogies* (A) to tell stories about the mechanisms, make analogies, and illustrate visuals;
- A *Context* (C) to place the mechanism in a biological or social setting; and
- The *How* (H) to describe the physical mechanism – how interacting biological entities produce activities across time and space at varying levels of complexity.

Participants interwove these four components into their explanation, and these components were combined to form the MACH model. Thus, the MACH model serves as a representation of the components that the biologists include when they explain

molecular and cellular mechanisms, and in so doing the results address the first problem of understanding the elements of explanation. The MACH model became the lens for subsequent studies to understand student explanations and to represent explanations for teaching.

1.2 Introduction to the second study and the teaching intervention

Chapter three features the second manuscript entitled, "Research to practice: Helping undergraduate students explain cellular and molecular mechanisms with the MACH model" (Trujillo, Anderson, & Pelaez, In preparationb). This study uses the MACH model as a representation in a teaching intervention. Given that the MACH model is a representation of the components experts in biology include when explaining, we wanted to know if teaching students to use the model would help them to explain as experts would explain. Thus, the second research study aims to understand the impact of using the MACH model as part of a teaching intervention by asking: How does using the MACH model change the explanations written by life science students? Why do students think learning about the MACH model is useful, if at all? In so doing, the second study extended the MACH model to teach the components of explanations used by biologists to explain molecular and cellular mechanisms.

A teaching intervention was implemented in an introductory biology course. By considering the messy nature of the classroom, a mixed-methods approach with an embedded qualitative study was appropriate to understand the teaching intervention. Quantitative measures were used to evaluate the change in the components used by students to create explanations. To address how student explanations changed, the presence of the MACH components were measured in a sample of students' written-work from exams before and after the intervention. By sampling students of different performance groups, inferences were made from paired comparisons about what changed as students participated in the intervention.

It was found that, before the intervention, most students in the course used all but one of the MACH components; they tended to include A, C, and H, but did not include the M in their explanations. This was insightful because the M component served as an indicator of how the students differ from the scientists; students tend to exclude the research methods in their explanation. After the teaching intervention, nearly all students used the four expert-derived components to create explanations. The intervention was successful since students were able to include all components.

To understand why the MACH was having the observed impact. With a qualitative approach, four students were recruited as key informants to be interviewed in order to understand why the explanations were changing across the intervention. Inductive analysis was applied to interviews and artifacts (exams, problem sets, and in-class activities) both within and across cases. Two student cases, Felix and Petunia are presented in detail.

The interviews revealed that students encountered varied difficulties in applying the model. For instance, Felix struggled to identify the Methods during the lecture and had to practice with the MACH several times before including this component. Additionally, an unforeseen difficulty was observed. Students failed to integrate the components into an explanations and instead treated each component as separate. Despite these difficulties, our students found that using the model (with practice) helped them to monitor their understanding, to create concise and complete explanations, and to identify gaps in their understanding.

This manuscript informs an understanding of how and why students change their explanations towards becoming expert-like. This research study gives insights into how to bring the knowledge of experts into a teaching and learning context, which informs the second problem. Additionally, it highlights the importance of mixed-methods to understand how a teaching intervention impacts students as a whole class and as individuals. However, this study raises new issues that future teaching interventions would have to address, namely, the issue of integrating explanation.

1.3 Introduction to the third study, an activity and a rubric

Chapter four contains the third manuscript, "Discovering pedagogical content knowledge (PCK) to help students understand how molecular and cellular mechanisms are explained" (Trujillo, Anderson, & Pelaez, In preparationa). This manuscript is written to those who teach biology. This chapter is situated in the theory of pedagogical content knowledge (PCK), which is subject matter knowledge for teaching. In our case, it is the knowledge of biological explanations for teaching. According to Shulman's original conception, PCK includes:

1. The use of representations to make the knowledge of a subject comprehensible to students, and

2. The understanding how students learn the specific subject including what aspects are easy or difficult to learn (Shulman, 1986).

The purpose of this manuscript is to communicate the PCK gained through our experiences with the teaching interventions and to document the developed resources for instructors to use the MACH model. The resources include a rubric, a tetrahedral model of MACH and an activity, which represent the knowledge of explanations in a form comprehensible to students. Both the activity and rubric were modified to address the difficulties of integration seen in the second study. With these products, other instructors may help students to integrate their knowledge and produce explanations with the MACH model, and in so doing, the teaching and learning of biological mechanisms can be brought in alignment with the explanations made by scientists of cellular and molecular mechanisms. The rubric is presented in this manuscript, while the tetrahedral model and activity can be found in both the appendices, as well as, in the Purdue International Biology Education Research Group ePubs collection (Trujillo, Anderson, & Pelaez, 2014b, 2014a). Both communicating PCK and sharing teaching resources will help other biology educators to teach students about the components used by biologists to explain; as such, this study is addresses the third problem of dissemination.

1.4 Introduction to the conclusion chapter

The fifth and final chapter ties the three inquiries into a complete interconnected view of the MACH model for teaching and learning. The purpose of this chapter is to make explicit the scholarly contributions of this PhD study. Chapter five contains a retrospective view for the reader of the research to interpret the work as it relates to the theory and practice of teaching science. In addition to the contributions of the whole document, a critical analysis addresses major limitations and areas for future research and teaching. For instance, the MACH model is a central outcome of this work but it is limited as a representation of the components of explanations made by the interviewed scientists. As an analytical framework, the MACH model has great potential for researchers, across many disciplines, to investigate a variety of media related to explanations including (but not limited to) lectures, videos, textbooks, and written, oral, and gestural communication of students, disciplinary experts, and educators. Additionally for educators, the model offers a way to teach students to explain molecular and cellular mechanisms with the teaching resources presented. Instructors may wish to extend the evidence-based lesson for use in their classrooms, further the design of the lesson, model, and rubric, or test the findings of these reports with their students. It is our hope that readers will extend this work to further the scholarship of research and teaching.

Overall, the dissertation can be summarized by one word: congruence. This dissertation project attempts to make explanations in the classroom congruent with the components used by scientists to explain molecular and cellular mechanism. Each study identifies a gap or incongruence and attempts to alleviate any discrepancy. I encourage the reader to trace these gaps to understand how the studies seek congruence. Throughout a variety of theories have been used including models of explanation, domain-specific expertise, and pedagogical content knowledge. Likewise a variety of methodologies and research frameworks were used including modeling, qualitative methods, mixed-methods, and pragmatic design to meet the respective purpose and

collect appropriate data for the studies. The research involved a range of scientists in several biology sub-disciplines, a range of courses across science departments, and a range of students of different performance levels to address the multi-faceted nature of explanations and to connect the teaching and learning of biological mechanisms to the practices of biologists. From these approaches, we achieved an understanding of the components used by different biologists to explain molecular and cellular mechanisms, produced a model of components to inform explaining in the classroom and, in turn, provided instructors with guidance to illustrate development of PCK and with resources for explaining in the classroom.

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CHAPTER 2. A MODEL OF HOW DIFFERENT BIOLOGY EXPERTS EXPLAIN MOLECULAR AND CELLULAR MECHANISMS

Authors: Caleb M. Trujillo, Trevor R. Anderson, and Nancy J. Pelaez

> Any intelligent fool can make things bigger, more complex, and more violent. It takes a touch of genius -and a lot of courage- to move in the opposite direction.
>
> *E. F. Schumacher*

Constructing explanations is an essential skill for all science learners. The goal of this project was to identify and model the key components of expert explanation of molecular and cellular mechanisms. As such, we asked: What is an appropriate model of the components of explanation used by biology experts when they explain molecular and cellular mechanisms? Do explanations made by experts from different biology subdisciplines at a university support the validity of this model? Guided by the modeling framework of Justi and Gilbert (2002), the validity of an initial model was tested by asking seven biologists to explain a molecular mechanism of their choice. Data were collected from interviews, artifacts, and drawings, and then, subjected to thematic analysis. We found that biologists explained the specific activities and organization of entities of the mechanism. In addition, they contextualized explanations according to their biological and social significance, integrated explanations with methods, instruments and measurements, and used analogies and narrated stories. The derived Methods, Analogies, Context and How themes informed the development of our final MACH model of mechanistic explanations. Future research will test the potential of

the MACH model as a guiding framework for instruction to enhance the quality of student explanations.

2.1 Introduction

Explaining a biological phenomenon effectively is a cornerstone of success in biology, and curriculum policy documents echo the importance of this ability (Brewer & Smith, 2011). When explaining natural phenomena, biologists describe mechanisms that regulate the behaviors of complex molecular and cellular systems, but explaining these mechanisms in the classroom presents a challenge due to their complicated, intangible, and abstract nature. There is a need to make the molecular and cellular mechanisms explained by biologists more comprehensible to students. To understand how biologists explain, here we address the following research questions: What is an appropriate model of the components of explanation used by biology experts to explain molecular and cellular mechanisms? Do explanations made by experts from different biology sub-disciplines at a Midwestern U.S. research university support the validity of this model? A valid conceptual model of components biologists include when they explain molecular and cellular mechanisms may help biology educators to both better understand the practices of science and better address the challenges faced by students

This report overviews the issues surrounding biological explanations and focuses on molecular and cellular mechanisms as a key type of biological explanation. For the purpose of the present study, *a biological mechanism explains how the component entities of a biological phenomenon interact at the molecular, microscopic, and macroscopic levels to produce detectable changes in state, activities, and spatial and temporal organization.* This definition was adapted from van Mil, Boerwinkel, and Waarlo (2013) who applied work in the philosophy of science to characterize the chemotaxis behavior of an *Escherichia coli* bacterium as an example. This definition provides a useful starting point to consider the content of explanations used

in biology in order to teach molecular mechanisms, but research is needed to find out if scientists across multiple biology sub-disciplines actually reason back and forth between cells and molecules as described by van Mil et al.(2013) in their model of molecular mechanism based on bacterial chemotaxis. Through a brief review of the literature, we first survey what it means to explain molecular and cellular mechanisms by comparing what scientists, science educators, and others have identified as challenges when explaining biological mechanisms. Then we propose and validate a model of explanations of molecular and cellular mechanisms for a variety of biological contexts with the ultimate goal of assisting educators in training biology students to explain in ways that are congruent with the practices of biology. Throughout this report we use the term "model" as a noun to refer to the conceptual representation of abstract components communicated by biologists when explaining molecular and cellular mechanisms, and as a verb to describe methods used to identify those components.

2.2 Background

Recent reports call for curriculum reform in the biological sciences in order to better prepare future scientists for doing research and to increase the science literacy of college graduates (Brewer & Smith, 2011; National Research Council, 2009). According to the *Vision and Change* report (Brewer & Smith, 2011), biological core concepts and core competencies should be taught at the undergraduate level including the ability to apply the process of science, to use quantitative reasoning, to model and simulate, to communicate and collaborate across disciplines, to tap into interdisciplinary approaches and to relate science with society. Among the core competencies, "A key recommendation is that biology courses and curricula must engage students in how scientific inquiry is conducted, including evaluating and interpreting scientific explanations of the natural world," (Brewer & Smith, 2011, p. xiii). However, despite

this focus on scientific explanations, these documents do not define what it means to create a scientific explanation.

Some biologists distinguish biological explanations by the types of questions that are being answered. According to Mayr (2004), biologists pursue two kinds of explanations: proximate causal explanations, which address "what" and "how" questions, and ultimate causal explanations, which answer "why" questions. Studies of proximate causes of molecular and cellular biology are grounded in a mechanistic model of scientific explanations, whereas ultimate causes are rooted in grander, more complex evolutionary theories. According to van Mil et al. (2013), when researchers explained the mechanism for chemotaxis in *E. coli*, they asked 'how' questions, subdivided activities based on function, generated plausible mechanisms, predicted activities from known entities, and predicted entities from known activities while focusing on organization. Their model of molecular explanations was based upon both a literature review and science research. They reflected on the work of Adler (1966) and Baker, Wolanin and Stock (2006) to explain how bacteria move toward chemicals. The model by van Mil et al. (2013) represents an explanation of molecular mechanisms based on a scientific investigation, using the heuristics of entities, activities, and organization from Machamer et al. (2000), but the model is based on only one example from biology research.

Some science educators who recognize biology recognize biology as a science that answers have identified a typical difficulty. Students conflate proximate causes ('how') with ultimate causes ('why') when explaining biological phenomena (Abrams & Southerland, 2001). In addition to this difficulty there are several other problematic characteristics of mechanistic explanations. First, unlike facts and procedures, mechanistic explanations are generally hierarchical and often have hidden causes, which produce an illusion of explanatory depth (Rozenblit & Keil, 2002). Likewise, depending on the familiarity of context to the student, student explanations of molecular behavior attribute cause at various levels of depth (Talanquer, 2010), and students often fail to transcend levels of biological organization when constructing explanations

about a biological phenomenon (Duncan & Reiser, 2007; Lewis & Kattmann, 2004). Second, mechanisms are often depicted with cartoon diagrams, and students tend to have difficulty relating such visuals to appropriate reasoning about explanations (Anderson, Schönborn, du Plessis, Gupthar, & Hull, 2013; Schönborn & Anderson, 2009; Tibell & Rundgren, 2010). Some reports have found that scientific explanations may blend with everyday explanations, which are often vague, idiosyncratic, intuitive and anecdotal (Treagust & Harrison, 1999). These everyday explanations may use semantics that address processes as governed by actors that have intentions such as letting, hindering, and helping (Talmy, 2000). Informal reasoning views processes as happening because actors have intentions and they use their abilities to achieve their purposes. In contrast, biological mechanisms are processes constrained by physical principles in systems at multiple scales from macroscopic to sub-microscopic levels.

In addition to the above-mentioned reasons why biological mechanisms may be difficult for students to learn, another problem stems from the current debate as to what constitutes a mechanistic explanation. A mechanistic model is one type of explanation based on identifying the underlying causes of a phenomenon, typically, by accounting for the physical entities including their properties and interactions, and the activities that cause a chain-like change in the organization of the entities and activities across time and space (Braaten & Windschitl, 2011). For example, growth factors signal cells to multiply when their organization and the activities of the underlying molecular entities cause changes. Russ, Scherr, Hammer, and Mikeska (2008) argued that a satisfactory definition of a mechanistic explanation is needed in science education, it is inappropriate to simply characterize mechanistic explanations as non-teleological formulations, simple causal explanations, or descriptions of the underlying structures. There is a need to apply these reports from philosophy and education to find out if practicing biologists follow a mechanistic model of explanation when they explain molecular and cellular mechanisms in the biological system they investigate.

In the present study, we approached our research by asking which model most accurately reflects how scientists really explain the biological mechanisms that they investigate. Both science educators and authors of curriculum reform documents would benefit from a clear model of how biologists explain molecular and cellular mechanisms. Clearly, there is agreement that undergraduate students who learn biology are expected to develop skills around explaining mechanisms so that they overcome such difficulties and become more expert in their approach to explaining science. Thus, a model of how biologists explain, if made available, could show students what it means to explain effectively to help them know when they fully understand a biological mechanism.

2.2.1 Research questions

The purpose of this study was to characterize how experts from different sub-disciplines of biology construct explanations about molecular and cellular mechanisms with the ultimate goal of improving student explanatory skills in this area. In so doing, we sought to gain greater insight into *the essential aspects of biology experts' explanations of molecular and cellular mechanisms by identifying components that apply to all of their explanations.* To do this, we addressed the following specific research questions: (1) What is an appropriate model of the components of explanations used by biology experts to explain molecular and cellular mechanisms? (2) Do explanations made by experts from different biology sub-disciplines at a Midwestern U.S. research university support the validity of this model?

2.3 Methods

The above research questions, were addresses with the modeling process of Justi and Gilbert (2002) as used by Schnborn and Anderson (2009) to guide our entire model development and validation process. Models, often used in science, are simplified purposeful representations of abstract ideas, complex processes, or phe-

nomena, and modeling is the act of developing a model. Justi and Gilbert (2002) proposed a model of modeling framework to depict the process of model development as an iterative process containing four stages. Mendona and Justi (2013) state that this approach to the modeling process provides important insight into both the essential concepts and the logical coherence of reasoning about concepts for scientific thinking.

The stages of modeling along with how each stage is addressed in this study are shown in Table 2.1. Stages 1 and 2 were done to address our RQ 1; stage 3 to address RQ 2, while stage 4 is dealt with in the final discussion section. Regarding stage 1, we decided that our purpose was to model the essential components of explanation that a biologist includes when explaining a biological mechanism. With this purpose in mind, we formulated an initial mental model based on the research literature on molecular mechanisms, especially the reports by van Mil et al. (2013) and Machamer et al. (2000). In stage 2, we expressed our model as a range of iterations of verbal and visual models, each time as per stage 3 testing them with various thought experiments and predictions. Stage 3 also involved checking if the model fulfilled its intended purpose by testing it with empirical evidence from interviews with biologists, as well as further thought experiments to come up with a modified, final model. In stage 4, the usefulness of this model was then evaluated by considering its scope and limitations.

Table 2.1.
Stages of the Justi and Gilbert (2002) model of modeling and their use in this study.

Stages of modeling	**Operations within this study**
(1) Decide on the purpose and formulate an initial mental model.	The purpose is to model the essential components used by biology experts to explain molecular mechanisms. An initial model was formulated based on the research literature on explanations and molecular mechanisms heavily informed by reports from van Mil et al. (2013) and Machamer et al. (2000).
(2) Express the mental model with material, visual, verbal or another mode of representation.	The model was expressed initially through a range of iterations of verbal and visual models.
(3) Test the model with thought experiments, predictions and empirical evidence to see what needs to be modified for it to fulfill its purpose.	Fulfillment of purpose was tested with empirical evidence from interviews with biologists and the model was further modified to produce the MACH model.
(4) Evaluate the scope and limitations of the model.	The usefulness of MACH model is addressed in the discussion to evaluate its scope and limitations.

2.3.1 Description of the initial mechanistic model

As described above, the initial model was grounded in the work of van Mil et al. (2013) and Machamer et al. (2000). As a first thought experiment, we considered how the components in the van Mil et al. (2013) model fit with explanations for both regulatory mechanisms of physiology as well as the transcriptional regulatory networks of developmental biology. According to the initial model, expert biologists giving mechanistic explanations identify relevant *entities* for the mechanism (e.g. protein complex, biomolecules, and organelle). Next, they might claim that the *entities* have a specific *state (e.g. phosphorylated, active, and methylated)*, which will then undergo a *state* change when the *entity interacts*. Experts will proceed to explain how these *states* change and begin talking about *activities*. The explanations may then transition from *activities* back to introducing *entities* in the mechanism, or the experts will begin explaining how the mechanism is *organized*. They will refer to what is happening over *time* (e.g. rates, sequences, and duration), how *entities* and *activities* are *organized in space* (e.g. orientation, localization, and compartmentalization), or they will switch between the *levels of organization* (e.g. molecular level and cellular level). By going between the three areas, *entities, activities,* and *organization*, the expert coherently explains how processes happen in the cell via proximate causes. For a visual representation of this initial model and its application to explain bacterial chemotaxis, see van Mil et al. (2013) .

2.3.2 Using a textbook explanation to exemplify the initial model

The initial mechanistic model was then applied to exemplify its usefulness as a tool for analyzing a textbook explanation and diagram from the textbook, Molecular Cell Biology (Lodish et al., 2000). For example, Figure 20-23 (Lodish et al., 2000) depicts part of the mechanism that explains how cells 'know' how to grow. It shows how epidermal growth factor (an *entity*) binds (an *interaction*) to its receptor (an *entity*) transcending the cell membrane (*spatial organization*). This binding allows

the receptors to dimerize (an *activity* due to *spatial organization*). Once the receptors dimerize, the receptors interact and activate each other through an enzymatic phosphorylation reaction (an *activity*), which causes a conformational change in the dimer (a *change in state*). With these phosphate groups attached (*state*), the receptors can recruit (*activity*) adapter proteins (an *entity*). The textbook authors continue,

> The adapter protein GRB2 binds to a specific phosphotyrosine on the activated RTK [the receptor] and to Sos, which in turn interacts with the inactive Ras GDP. The guanine nucleotide - exchange factor (GEF) activity of Sos then promotes formation of the active Ras GTP. (Lodish et al., 2000)

These actions create a signal cascade that eventually activates transcription of genes involved in proliferation.

The textbook author's explanation of this mechanism exemplified the initial model and provided us with a starting point to discuss and explore other explanations of molecular and cellular mechanisms. Our question (RQ 1), though, was whether this model would also represent how expert biology researchers explain mechanisms, or would the approach prove only applicable to textbook author-type explanations? This issue was investigated through interviews with our selected biology experts (RQ 2). At the same time, the empirical data from the interviews, as well as our own intuition and thought experiments (Justi & Gilbert, 2002) enabled us to use components of the initial model to develop several modified models for mechanistic explanations in biology (RQ 2).

2.3.3 Selection of participants

Seven biology expert biological research scientists from a large Midwestern public research university in the United States were recruited for this study. By studying multiple experts in related but distinct fields of biology, we sought to make explicit those components of their explanations that contain knowledge across the

sub-disciplines of biology, so that we may find consensus themes across the sub-disciplines. Thus, the participants were selected purposefully, based on two criteria used for theoretical sampling (Patton, 2002). First, the participants had to be faculty members of a biology department who had done research on a molecular or cellular mechanism and had published their findings. Second, the selected biologists had to be from a range of biology sub-disciplines that study molecular mechanisms. In this way, a range of biological perspectives from different sub-disciplines that deal with molecular mechanisms could be synthesized to inform components of mechanistic explanations that apply to all of their explanations. Table 2.2 gives biographical information about the participants, including their number of years of research experience, their fields of study, and the research questions they address. Hereafter we refer to these participants as biology experts.

Although the participants represent a variety of sub-disciplines, some fields within biology are absent. For instance, researchers of biochemistry, plant biology, computational biology, and other mechanistic fields have been excluded. This is a limitation discussed below. Pseudonyms were used to protect participant identities and research was performed under the approval of the Institutional Review Board (Protocol number: 120301239).

Table 2.2.
Participant research scientists and their various sub-disciplines of biology.

Pseudonym	**Field of study**	**Laboratory's Research Question**	**Experience in Years**
Darth	Neurobiology	What are the cellular mechanisms that shape auditory processing?	19
Sally	Cancer biology	How does a transcription factor affect cell behavior?	37
Molly	Physiology	How does calcium signal smooth muscle contraction?	12
James	Developmental and cancer biology	How does gene expression affect cell function?	36
Jay	Structural biology and biophysics	How do viruses assemble in a cellular environment?	8
Frank	Neurobiology	How are organelles transported within the axon?	34
Buck	Cancer biology and physiology	How do hormones from fat tissue promote or repress cancer growth?	16

2.3.4 Description of the interview protocol

The biology experts participated in semi-structured interviews of 50-120 minutes duration. This qualitative approach allowed us to describe in detail and depth how expert biologists explain mechanisms, thereby facilitating the testing of the initial model and subsequent modifications thereof to reach our final model. A major part of the interview involved openly prompting the participants to explain a mechanism of their own choice (modified from Schönborn & Anderson, 2009). The interview commenced with the following guiding statement:

> Today I would like you to talk about cellular mechanisms. Take your time and start thinking about these types of processes. Take as much time as you want, don't rush, just relax and think about them for a while. Try to imagine it; mechanisms inside the cell, think about everything you know about *what* these are and *how* they work. Ok, what are you thinking about now? Tell me slowly and clearly. Take your time.

This statement was intended to focus participants on explanations of molecular and cellular mechanisms by prompting them to explain 'how' these work rather than 'why' they work. Furthermore, the participants were encouraged to explain the mechanism they knew best, having extensively studied it in their research.

The purpose and methods of the study were made explicit before enrollment in the study. The interviewer was perceived as a fellow biologist (trained in developmental biology) rather than as a student, but not with expertise in the same discipline as the expert who was interviewed. Interviews are dynamic and the researcher attempted to come to an understanding of the participant's explanatory knowledge by probing to co-construct shared knowledge during the interview as might happen during a conversation between two scientists. Member checking was integrated into the original script, such that during the interview, the researcher would repeat back the key points of the expert, and then the participant researcher would confirm the summary and clarify or expand the explanation (Lincoln & Guba, 1985).

2.3.5 Data collection and processing

The data consisted of transcribed audio-recordings of the interviews, written notes taken by the interviewer, as well as drawings and artifacts produced by the respondents during the interview. The transcribed data were analyzed qualitatively using NVivo data analysis software (QSR International Pty Ltd. Version 8; 2008). The data set of interest was limited to the sections of the transcript in which participants provided an explanation of a mechanism studied in their research (i.e. background information and other speech not addressing the research question was excluded). Thematic analysis as described by Braun and Clarke (2006) was used to construct themes and patterns that fit the explanations of the experts. Analysis occurred concurrent with data collection such that interviews continued until the themes reached saturation (Lincoln & Guba, 1985). Additional interview data were redundant after the fifth interview of the seven biology experts when it was found that the additional interviews were no longer revealing new themes or insights. The themes were reviewed as per Attride-Stirling (2001) by constructing and reconstructing thematic networks with the codes, categories, and themes. These themes provide the evidence for the validation of our final model (RQ 2). Once data were collected, multiple colleagues assisted in the analysis of the data during weekly meetings with the co-authors and debriefing meetings with a larger research group. In addition, the participant biologists corroborated findings by reviewing the results of the research report for accuracy and clarity (Lincoln & Guba, 1985).They edited the grammar of their excerpts during a final member checking session to improve readability from the colloquial transcript; these *post-hoc* edits did not affect the analysis or findings.

2.4 Results

2.4.1 Validation of the initial model with expert explanations from different biology sub-disciplines

To address RQ 2, we constructed themes from the explanations provided by the biologists. As expected, we found that components included in expert explanations were predicted by the initial model. In addition, though, their explanations also included features not associated with the initial model, leading us to modify it to the final model presented later. Four major themes emanated from our analysis of the transcribed interview data. It was found that our biology research scientists used the following components when they explained biological mechanisms:

- They used the initial model of mechanistic explanation by focusing on entities, activities, and organization ("How" Theme);
- They highly contextualized and constrained their explanation according to biological and societal significance ("Context" Theme);
- They integrated explanations with the methods, instruments, and measurements they use to investigate their mechanism ("Methods" Theme); and
- They used narrative stories along with analogies to explain their systems ("Analogy" Theme).

The interview data revealed that these themes operate together when biologists construct thorough mechanistic explanations of the systems that they investigate. Below we present supporting empirical data for each of the above themes and show how the different biologists that we studied used the strategies and knowledge represented by each theme to do mechanistic thinking. The excerpts below offer representative quotes of each theme. Each of the seven biologists' explanations contained all four themes. These themes allowed us to test and modify the model with empirical evidence towards fulfilling our purpose.

The 'How' Theme: Biologists focus explanations on the entities, activities, and organization of the mechanism.

From analysis of the interview transcripts, it was clear that our sample of experts dedicated a significant amount of talk to the mechanism of interacting biological entities. Ubiquitously, the experts refer to what the states of those entities are, how they interact, and how they induce other entities to change states. For example, Sally, a cancer biologist, explained signal transduction via the epidermal growth factor (EGF) pathway. She states,

> EGF binds to its receptors and brings them together, the purpose of bringing them together is to activate the receptor kinase domain, so when they come together that they first act on each other to provide the right phosphorylation to activate the kinases. Then, these guys become phosphorylated all over the place, and that forms sites for proteins to dock. Protein X comes on here, protein Y comes on here, [. . .] and that docking obviously provides access to additional signals (Sally, line 238-46).

In Sally's explanations, the EGF, receptors, domains, and proteins represented the entities. The receptors changed state by coming together and becoming phosphorylated, which induced the receptors to have activity. In this case, the activity was to change the state of other proteins. Note that this molecular level explanation used terms like "dock" and "bind" to describe the interactions. This analysis was strengthened by the diagram made by Sally while explaining the EGF pathway (Figure 2.1A). A focus on these parts of the initial model was common among the biologists we interviewed, and explanations included how the activities and entities were organized.

Consistent with the initial model, the experts integrated their explanations of entities and activities around three types of organization of their chosen systems. Temporal organization, spatial organization, and the multiple levels of biological organization were important considerations to the experts both implicitly and explicitly.

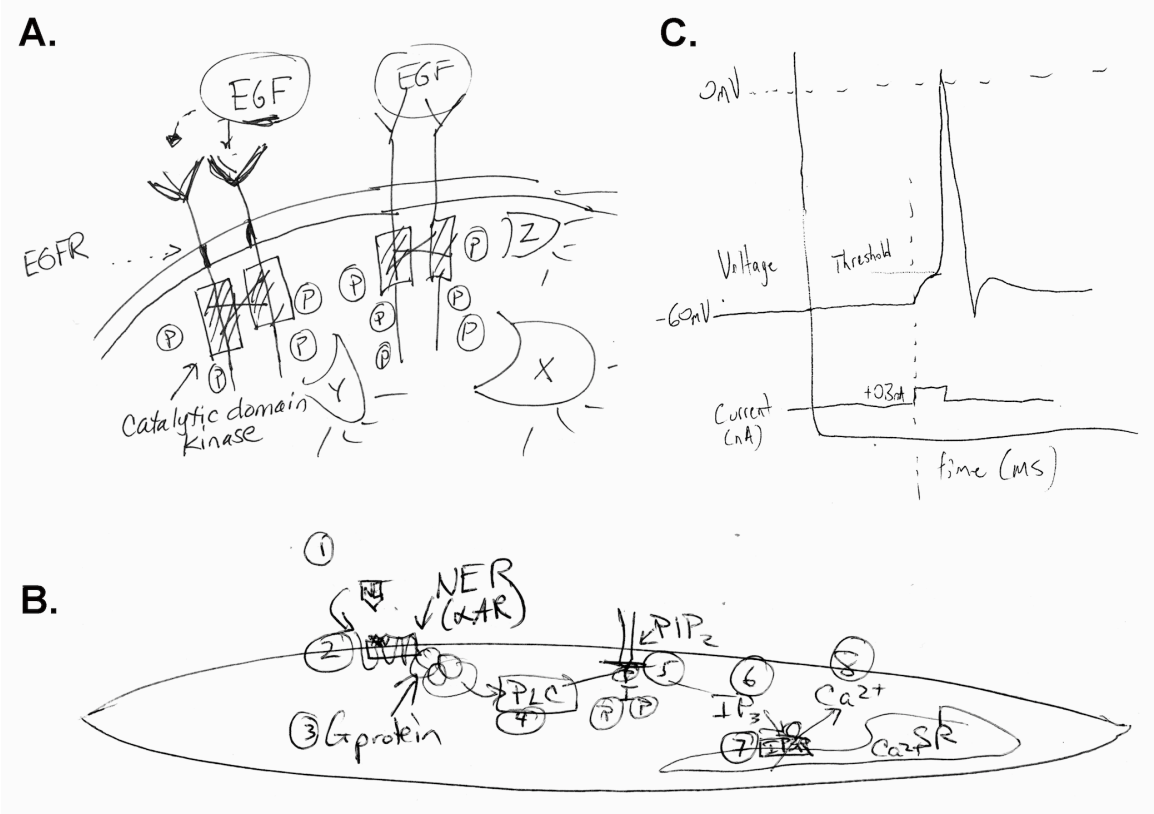

Fig. 2.1. These illustrations are typical of drawings made by scientists as they explained a mechanism they investigate. Panel A shows a diagram of the EGF signaling mechanism by Sally indicating a model of signal transduction that plays a role in cancer. Panel B shows a schematic diagram by Molly of the mechanism that releases calcium to regulate contraction of a vascular smooth muscle cell. Panel C is a graph by Darth displaying the mechanism of an action potential of a neuron.

For example, as a structural biologist, Jay explained the system with which he works (i.e. viral assembly):

> Very specific reactions are occurring at specific locations, and as we look at higher and higher resolution, these chemical reactions can only occur if their concentrations are driven up in specific areas. I often think of this like real estate that is the location is the key, [. . .] the biological chemicals need to be at the proper spot, and they have to be there at the right time, so it is this really coordinated event. [It] is not actually three-dimensional. [It] is four-dimensional; you have timing and location, all come together for these events to occur. You don't want RNA to come off of here and go throughout the cell because you know that could be wasted energy it may not find coat protein. Viruses don't want to waste energy just like the cell doesn't waste energy (Jay, line 312-25).

In Jay's explanation, there was a specific focus beyond just the "biological chemicals," which is to say the entities. Jay pointed out that "location" and "timing" drive biological events. Succinctly Jay proclaimed, "It is this really coordinated event. [It] is not actually three-dimensional. [It] is four dimensional". Both spatial and temporal organizations were distinct as aspects of mechanistic explanations.

Explanations from our participants commonly discussed temporal organization. For instance, Molly extrapolated on the mechanism of how norepinephrine signals lead to the shortening of vascular smooth muscle cells when asked to draw her internal representation (Figure 2.1B).

> Molly: Here is my G protein coupled receptor which is a seven transmembrane receptor. Here is the G protein. Here is norepinephrine, so it binds there [the receptor]. Here is phospholipase C, this comes off and binds there, phospholipase C then cleaves off this I with a phosphate here, a phosphate here, and a phosphate there, it cuts here and then you get this IP3. The SR [Sarcoplasmic reticulum] has calcium inside. And then

> here is the IP3 receptor so when IP3 comes across and binds here calcium comes out.
>
> Interviewer: And what do those arrows represent?
>
> Molly (while numbering diagram): The sequence of time. Therefore, it is basically, here is the first step, [...] the rise [in] norepinephrine. Here is the second step binding to the alpha androgenic receptor and here is the third step the G protein gets activated, and then here is the fourth step. It is phospholipase C becomes activated. And here is the fifth step. It would be cleavage of IP3. (Molly, line 167-84)

As before with Sally, Molly used entities, interactions and activities, but this explanation also considered temporal organizations. Molly used the diagram of norepinephine's action to represent the sequence of events symbolically. The "arrows" of the schematic diagram represented steps in time, rather than precise spatial movements. Temporal organization was a key part of both the excerpts from Jay and Molly, and these were representative of the other experts as well, who also considered time and space as two of the three ways mechanisms are organized.

A third way our experts considered organization was across multiple levels of organization. The developmental biologist, James, explained the function of secretory cells in the pancreas:

> We work on cells called pancreatic ascinar cells and these cells secrete digestive enzymes. To accomplish this they have to maintain a cell polarity, where they have a distinct apical and basal boundary and intracellular organization of organelles so that they synthesize the protein at the correct location. At the apical surface are granules called zymogen granules that package the digestive enzymes, so when you eat, you get a signal from a hormone, known as CCK, Cholecystokinin, that binds to a receptor that is on the basal surface of these cells. There is a calcium wave that goes through a complex signaling cascade, but eventually these little zymogen granules fuse with the plasma membrane and therefore release their di-

> gestive enzymes. And then those digestive enzymes go through a duct system, [. . .] that comes out into what is known as the pancreatic duct and that feeds into the intestines (James, line 75-89).

James explained his chosen system lucidly and readily translated vertically (Schönborn & Bögeholz, 2009) between many levels of biological organization. He began with cells, zoomed down to the organelles, then molecules (i.e. enzymes). After the molecules, he identified zymogen granules, which are cell structures, and then zoomed out from the receptors, to the pancreatic ducts and organs. This kind of transcending explanation was typical throughout the interviews with the biology experts, who without hesitation readily translated through different orders of biological organization and scale when discussing their mechanisms. To answer research question 2, overall, the initial model captured each of our participants' explanations, since there was pervasive use of entities, activities, and organization by the participants, thereby confirming the representation by van Mil et al. (2013) and supporting the fact that these components should be retained as part of any modified model. However, the results from our interviews also revealed several other notable themes, which allowed us to significantly modify our initial model to better represent the explanations used by experts in this area.

The 'Context' Theme: Biologists contextualize explanations by considering biological and social relevance.

The initial mechanism model did not capture the great deal of contextualizing that experts exhibited. We found that the biologists we interviewed always considered a context in their mechanistic explanations. That is, they considered the biological systems they explain. This is because mechanisms are rooted in the cell type, organism, evolutionary history, and other biological contexts. For instance, Sally observed, "These signals (growth factors)[. . .] go and tell the other organelles what to do in response to the signal, and that is what varies from cell to cell" (Sally line 247-9).

She qualified her explanations to emphasize that the mechanism varies depending on the cellular context. Furthermore, Frank, a neurobiologist explained his laboratory's system of choice:

> You can mutate or knockout in a fly the same gene that gives a human who has that gene mutated or knocked out a specific disorder. We work with flies that have the same mutation in the frataxin gene as humans with Friedreich's ataxia. Now [we are] working with flies that have the same mutations in the parkin or pink1 genes that people with hereditary Parkinson's disease do. Now it is not that a fly [is] great model for a human being getting Parkinson's disease. It is that we are looking at what happens at the cellular level. It's about what is the cellular neuropathology in a neuron in an intact nervous system, even if it is a fly (Frank, line 111-6).

Frank distinguished several contexts in this excerpt. First, he pointed out which organism his lab uses, *Drosophila* (fruit fly), and justified its use as a model organism to understand another organism, namely humans. Second, his explanation related to the broader context of human health, to the disorders he wished to understand, namely Parkinson's disease and Friedreich's ataxia. Finally, Frank's explanation returned to the cell type being used by stating, "the cellular neuropathology in a neuron." Thus, both the biological context of the mechanisms and its context in society were associated with the biologists' explanations. Overall, the research scientists' explanations featured highly contextualized mechanisms, suggesting that context was an important component of our modified model.

The 'Methods' Theme: Biologists insinuate explanations with the tools, methods, and measurements of how they know.

A ubiquitous characteristic of the explanations that we obtained from the participant biologists was a consistent reference to methods they use in their respec-

tive laboratories. The biologists contextualized the mechanisms they explained by the methods, tools, and practices they use to generate the data that inform their mechanism. Darth's explanation of action potentials illustrated just how entangled instrumentation and explanation were. He went into great depth while explaining the sequence of ion channels opening during an action potential and drew a graph to represent the phenomenon (Figure 2.1C). Darth, a neuroscientist explained,

> I've recorded these in a lot of different ways, so I can also imagine an oscilloscope trace, and also in vivo, the extracellular trace. [. . .] This would be what an electrode sees if you recorded intracellularly, so let's say with a patch clamp electrode, but often with our metal microelectrodes, we record action potentials extracellular and then they have a different waveform. (Darth, line 552-6)

Darth's explanation considered the electrodes, oscilloscope, placement, and type of sample (*in vivo* vs. *in vitro*). Furthermore, Darth's graph was how he visualizes the mechanism, not as a schematic model, but grounded in the techniques and instruments used in his lab. His thinking about what the mechanism is and how we know the mechanism were inseparable. This trend of focusing on measurements and laboratory practices was also well articulated by Frank on the topic of organelle movement in the synapse. He reflected,

> Some people would say that all the mitochondria headed for the synapse, they go 0.35 µm per second [...] At the synapse, which needs mitochondria to arrive there, it cannot tell how they got there. [...] To be teleological, all the synapse cares about is how many cross this line per unit time. So often we find that flux measures, just putting a mark down and saying how many mitochondria cross that line [...] per unit time, that sometimes is the most interesting thing, because that obviously integrates how fast they are moving and how much of the time they move. (Frank, line 372-9)

Frank's constructed explanations took into account the limitations and strengths of different methods. For him, understanding the activity of the mitochondria in the neuron was intimately related to the way the measurements were taken. Measuring flux was Frank's way of combining the activity and spatial organization of the axonal transport mechanism. The excerpts represent the tight linkage between the explanation and methodology used in their laboratory practices, suggesting that this aspect would be an important component of any modified model.

The 'Analogy' Theme: Biologists use stories and analogies when explaining mechanisms.

Within each explanation, we found that the biologists that we interviewed used narrative forms along with scientific models and analogies. The use of representations, a type of analogy (Clement, 1988), is evident in the artifacts of the participants; Figures 2.1A and 2.1B show schematic diagrams that were typically seen with mechanistic explanations. Molly used scientific models to structure her explanation and was able to consider the limitations. She states, "I know the model is flawed because I can think of data that raises questions about parts of the model" (Molly, line 86-87). Molly connected her model of norepeinephine's action to the data.

Scientific models were not the only way biologists made sense of explanations. The participants also used other analogies in their explanations; these analogies communicated their knowledge about the submicroscopic world. For instance, Jay highlighted that the research that has been done before "would kind of be like watching a car be put together but outside of the factors" (Jay, line 203). Jay communicated the distinction of studying a system in vivo versus in vitro using a factory assembly analogy. There were also many other analogies used in a variety of ways. For instance, James communicated the concept of modularity of biomolecules using a popular toy as an analogical model by stating:

> We can take two proteins. I can take the DNA-binding domain of one protein and put it on another protein and that DNA-binding domain will work. To me, that is unbelievable. I just take a chunk of amino acids, of protein, and stick it on this [. . .] and it works. It is like Mr. Potato Head. You can stick on the arm of Mrs. Potato Head, and it works. (James, line 389-94)

Making analogies was clearly a creative way our biology participants adorned their explanations and they often helped them illustrate the links between the molecular world and the macroscopic world.

Surprisingly, participants also used teleological and anthropomorphic formulations and more general narrative stories to explain molecular and cellular mechanisms. By teleological formulation we mean backward causation. For instance, the explanation may focus on the end-result of the mechanism, the purpose, or needs (see Zohar & Ginossar, 1998). Among the analogies used, our experts attributed human characteristics to non-human objects, which is to say they anthropomorphize the mechanism (see Zohar & Ginossar, 1998). For instance, Jay introduced the purpose of his research by explaining:

> [With a] segmented genome, the virus needs to know the virus has three [DNA] segments. It has to somehow determine that it has packaged all three segments to form an infectious virus. So somehow, viruses have developed a mechanism for counting, which is interesting at the structural level. This virus can go, 'Yep, got them, all three. Okay, we are ready to leave the cell.' (Jay, line 189-92).

Jay and many of the other scientists assigned anthropomorphic actions to their entities during the explanation. In this case, Jay used both. He first focused on the purpose of viral assembly, and then he attributed the viruses with the ability to "know" and to "count". Teleological statements are also common in other explanations. For instance, Frank explained, "You have most of the mitochondria stationary [...] they're

piled up at Nodes of Ranvier where you have all this ion pumping, and guess what, you need a lot of ATP. That sort of makes the kind of common sense in a way. [...] Put it where you need that function" (Frank, line 195-200). In Frank's case, the organization and activity of the mitochondria were extremely important for other functions. The "common sense" to which he was referring is the idea that the needs of the system helped him make sense of what components will be used. We expand on this later during the final discussion.

The interviews and analysis showed that narrative forms of explanations, including the use of teleological reasoning and anthropomorphic characteristics, were present in the explanations of our participant researchers, and accompanied by analogies and scientific models. These findings suggested the importance of including these aspects of explanation in our final model.

Exceptions within themes

While thematic analysis can capture succinct ideas from the data, the themes may overlook unique cases and disconfirming evidence. This section elaborates on the data that did not fit the abovementioned themes but yielded important insights worthy of noting.

Explanations gave variable emphasis to some feature of our initial model. First, most biologists associated activities with state changes; these typically meant a chemical or conformational change to a protein or other property and entity. State changes involved changes in both space and in time. However, Jay, the structural biologist, infrequently described temporal changes in state, instead focusing much of his explanation on spatial features at the molecular level. When Jay discussed protein interactions to do with the structure and position of viral assembly, he did this in terms of their orientation and location. He states, "They have to be there at the right time" (Jay, line 321). Based on information about location, a temporal sequence was inferred. Thus, activities (e.g. turning off and on) did not characterize his explana-

tion; the entities did not change in this way. Rather, the entities changed through spatial organization, by stages of assembly. In contrast, Sally ignores molecular location and orientation when she states, "these guys become phosphorylated all over the place." Instead, Sally emphasizes the temporal sequence of events when she states, "they first activate the kinases" (Sally, line 240-41). We attributed this difference in their explanations to the fact that Sally, as a cancer researcher, has a different perspective from the structural focus Jay employs as a researcher. Changes in entities and organization were included to different degrees when the participant biologists' explanations were compared to the initial model.

Second, we noted that our interviewees used levels of organization in different ways. Jay, for example, remained primarily at the molecular level, while Sally explained across multiple levels but did not envision the molecular scale. For instance, she stated, "I don't see any carbon bonds anywhere, even DNA. I don't see [a] carbon bond. I just see a double helix. I don't see bases or anything, I would just see a helix" (Sally, line 388-9). Sally also did not imagine movement at the molecule's timescale. However, Sally's explanations integrated organization at the higher levels. For her research program, thinking about intramolecular features was not useful. These observations point out that some of our biologists prefer a particular level of organization. The researchers found a particular level useful for their particular research questions. These results suggest that the initial model will not perfectly represent experts' explanations; emphases for the components varied in explanations from diverse experts. The components (i.e. themes) are present but at different depths and with some degree of flexibility.

Third, within the theme of context, societal contextualization gained the least support compared to biological context. While each participant drew connections to the societal significance of, for example, knowledge of disease, this happened infrequently (1-3 times per participant) compared to biological context of the theme. This finding is understandable; most scientists would be expected to focus more on

their immediate context (e.g. the organism) than that of broader context areas (e.g. human health) when generating an explanation.

Fourth, regarding the analogies and narrative forms of explanation, some of our interviewees used metaphors that were unscientific in nature. When using teleological and anthropomorphic explanations, they would often point out the limitations of their thinking. For example, James used the term 'know' when describing the cell in general and when asked to elaborate stated the following:

> James: This [replication] machinery is very complicated. The cell has to bring in the correct ribonucleotide. It has to know that the next one should be an A, and not a U, not a G, not C, but an A, so it has to know that. It has to figure that out. Knowing is probably not the right term but it has to figure it out how to make sure the right ones there. Then it has to be ligated [...]
>
> Interviewer: You used the term 'know' and then you corrected yourself [...]
>
> James: I don't think cells think like we do, and I do that all the time, I catch myself saying that all the time in the classroom. [...] I like to talk about cells like they are people, you know like they have personalities. We actually use those terms in the lab all the time to say our cells look good. You know it is not very scientific. Are they smiling at you today? When you look under the microscope, they look good, but that is not a very precise scientific term and I often will say things like they have to know when to divide, you have to know when to differentiate. (James, line 192-217)

James emphasized that, even though he used anthropomorphic characteristics to describe cells, he was not doing so in a "scientific" way. This language was in his lab and in the classroom. He pointed out that there are different levels of precision that the explanation can provide. This example shows us that the biologist's explanations contain ways of telling their story that are less precise versions of mechanistic

explanations. In conclusion, we discovered from the data that there were clear variations between individual biologists in how our participant sample used the various aspects of explanation. This is not surprising given the intrinsic differences between the biology sub-disciplines and the variation between humans.

2.4.2 Modifying the initial model into a final model: Fulfilling the purpose of the model

To summarize, the empirical data obtained from biology experts at one Midwestern U.S. research university led to our identification of the following four major themes composing their explanations about molecular and cellular mechanisms:

- Our participant biologists acknowledged limitations to the mechanism based on how they learned about it using tools, measures and methods ('Methods' Theme);
- They explained why the mechanism happens through a story or analogy ('Analogy' Theme);
- They contextualized their explanation to show how it was useful ('Context' Theme); and
- They explained how the mechanism works by identifying entities and their activities and organization ('How' Theme).

These identified themes permitted us to look at the initial model with "new eyes". First, we realized that the initial model corresponded to the "how" theme and was, therefore, a valid component of expert explanation. Indeed the initial model foretold a substantial amount of the explanation provided by the experts in that interacting entities, activities, and organization are important aspects of molecular and cellular mechanisms. The interviewed experts explained what the states of the entities are, how they interact, how the entities and activities are organized in time

and space, and what the relationships are across multiple levels of organization. Second, we realized that the initial model did not accommodate our other three themes. This observation informed the decision to modify the initial model into a final model, which we term the MACH model (Figure 2.2). In our view, this model with its four components shows how the themes fit together when experts formulate a complete explanation of molecular and cellular events. In view of the interactive nature of the four components of the MACH model, in that explanations can compose a range of combinations of component factors, we considered several possible ways of representing this model but, for multiple reasons, finally settled on a Venn diagram. Venn logic, which is based on set theory, conveniently illustrates how for example experts not only explain mechanisms according to the "How" (H component) theme (as per the initial model) but also ground their explanations in Methods (M component), Analogies (A component) and the various Contexts (C component) of relevance to the particular mechanism. In Table 2.3, we propose operational definitions for the components of the MACH model. The Venn diagram and definitions of the MACH model serves as a representation of the components biologists from various sub-disciplines consider when they explain molecular and cellular mechanisms.

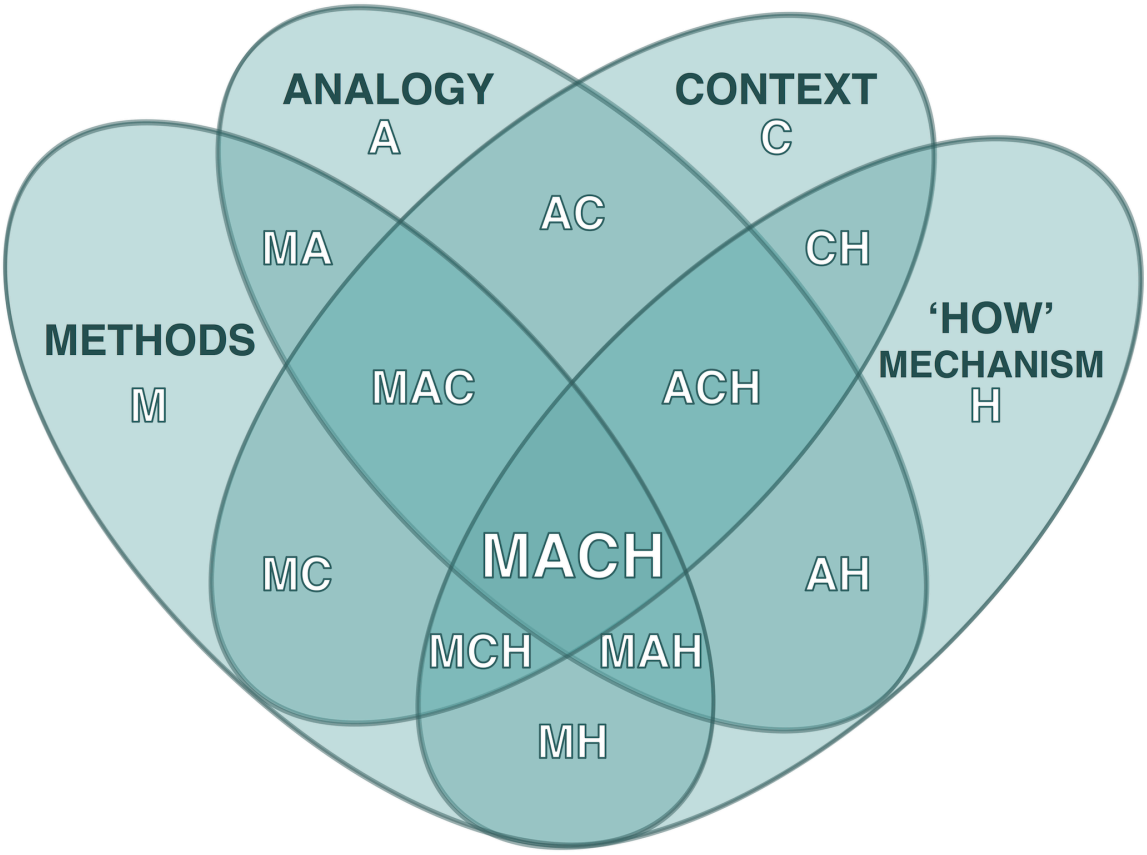

Fig. 2.2. The MACH model of explanations. A Venn diagram representing the components of explanations based on themes from interviews with research scientists: the Methods, the Analogy, the Context, and the 'How' of the mechanism. In this study, all of the biologists' explanations are represented by MACH and contain all of the components.

Table 2.3.
Operational definitions of the four MACH model components.

Component	**Symbol**	**Operational Definition**
Methods of Research	M	The tools (e.g. instruments and devises), data (e.g. measurements and instrument readings), or procedures (e.g. methods, protocols, and techniques) used to generate evidence that informs the explanation and qualifies or limits the generalizability of interpretations.
Analogies and Stories	A	The stories and analogies that make sense of and relate to a purpose for the mechanism with formal analogies, models (e.g. representations, diagrams, graphs, etc.), or narrative forms (e.g. teleological and anthropomorphic statements).
Social or Biological Context	C	The biological context (e.g. a specific cell, tissue or organ type, groups of organisms and their evolutionary history), or social concerns including human health and disease, which connect the explanation to a setting where it can be fully applied and understood.
How the Mechanism Works	H	How the component entities of a biological phenomenon interact at the molecular, microscopic, and macroscopic levels to produce detectable changes in state, activities, and spatial and temporal organization

2.5 Conclusion and discussion

In this project, we addressed the following research questions: (1) What is an appropriate model of the components of explanation used by biology experts to explain molecular and cellular mechanisms? (2) Do explanations made by experts from different biology sub-disciplines at a Midwestern U.S. research university support the validity of this model? Findings presented in this paper suggest that we have indeed developed and validated an appropriate model of explanations made by biologists who investigate molecular and cellular mechanisms at one Midwestern U.S. research university and thereby achieved the purpose of the modeling process defined by Justi and Gilbert (2002). Building upon the mechanistic model of explanations by van Mil et al. (2013), the MACH model brings refreshing clarity to what it means to explain 'how' in biology.

Our analysis suggests that there was a high amount of contextualization when explaining biology (Context Theme). As seen in other research examining expertise in other disciplines (e.g. M. T. Chi, 2006), research scientists qualify and constrain the extent of generalization and focus more narrowly on specific contexts. Indeed, our biologists demonstrated that explanations have limits and these limits revolve around biological context and the relevance to society. Repeated and interwoven references to methods, data, and instruments that have informed the mechanism are another way that our biology experts imposed conditions or limits to their explanations (Methods Theme). Our participant biologists all grounded their explanations in the types of questions their labs are asking and the tools used in their research to answer these questions. The variety of methods used by the scientists of different sub-disciplines in our study gave the explanations different flavors. For example, the structural biologists explained the molecular interactions within the mechanism of interest, but the cancer biologist did not. For the structural biologist a sequence in time for building viruses in a cell is based on spatial distribution data for particular types of molecules. Thinking about temporal sequence is more useful than thinking about locating molec-

ular interactions for the type of research the cancer biologist does. Constructing explanations around their instrumentation and laboratory settings comes from their extended experience and practice as biology researchers, which is to say their domain specific expertise. Thus, different methods utilized in mechanism research produce different explanations of mechanisms. Our work shows that explanations interweave with and are inseparable from the practices of life scientists.

Another point worth consideration is the use of analogies. Previously, Clement (1988) reported that scientists, when they solve physics problems, spontaneously create analogies. Findings reported here confirm the notion that expert scientists use analogies (Analogy Theme), in this case when explaining the changing activities and organization of entities for their mechanism. Additionally, scientists in our study used scientific models as a type of analogy (Duit, 1991; Grosslight, Unger, Jay, & Smith, 1991). Scientific models allow life scientists to focus their explanations on a few components and the organization of those components (as Molly exemplified above). The stories and analogies used by experts allow them to structure explanations effectively and, as Frank observed, find the "common sense" in the information. The fact that our experts were using analogies suggests we should not dismiss these types of explanations as unscientific.

Some of our experts combined the 'why' with the 'how' in their explanations. They considered the ultimate purpose when they explained how their mechanism works. This was apparent in their use of two other types of analogies, anthropomorphic and teleological statements, which were used in an attempt to provide reasons as part of an explanation. In considering how biologists' explanations intermingle proximate causes with ultimate causes, it should be noted that this has also been seen with students at many age levels (Abrams & Southerland, 2001). Garvin-Doxas and Klymkowsky (2008) found that many undergraduate students explain biological processes using directed actions, resulting in explanations that resemble backwards causation. In other words, when students overlook the role of randomness in a multitude of biological processes, they focus on the benefits of the effect and not the

cause. Rather than being wrong and a hindrance to learning, the findings reported here support the idea that teleological and anthropomorphic explanations are less precise explanations used even by experts who can provide full mechanistic details. Treagust and Harrison (1999) suggested that anthropomorphism, teleology, analogy and metaphor are pedagogical tools for explaining. Zohar and Ginossar (1998) reported that teleological and anthropomorphic arguments had useful heuristic value for learners, and students were able to distinguish between causal and less precise formulations, which is precisely what James did when he said, "I like to talk about cells like they are people, you know like they have personalities [...] you know, it is not very scientific." In this sense, the scientist used informal language to explain the biological mechanism as if it were caused by an actor with needs and purposes. Analogical diagrams or stories were used to explain how needs were met to achieve the purposes for the mechanism the scientists described (Talmy, 2000). In light of the final model, the fact that students explain biological processes using directed actions is consistent with what experts do when they create analogies and formulations to help explain a sequential story around biological functions, purposes, and outcomes.

The multi-component nature of the MACH model allows for partial explanations that do not constitute all the components of the model. Thus, it will be possible to test the efficacy of this framework beyond our experts to other experts in biology and other sciences and particularly to students who are less likely to use such complex explanations when discussing mechanisms. The MACH model could also be used to account for variation in sequence and integration of the four components and also which facets of explanation are receiving greater emphasis. The model highlights and alerts one to implicit components even if not woven into an explanation.

2.5.1 Limitations

As with all research, the findings presented here have limitations. First, we must highlight the nature of our sampling. Data were collected only from biologists

who investigate molecular and cellular mechanisms at a single Midwestern U.S. research university. The MACH model currently only applies to the explanations of molecular and cellular mechanisms from the experts in our study. Different methodologies would be required to generalize the ideas presented herein to all life scientists. For example, several sub-discipline fields that work with mechanisms were not included in our study. Plant biology, biochemistry, microbiology, or systems biology may explain their systems with insightful approaches that may be dissimilar. As another example to indicate limits for the scope of our findings, our data does not allow us to find out if social context was mentioned by our experts due to influences from their funding situation, since all participants in our study have attempted to convince funding agencies with grant proposals to support their research. Because of the sampling limitations, the model still needs to be tested to understand if it applies to explanations made by other biologists including scientists in industry, those from diverse cultures, or to determine how the model would work when viewed from a feminist perspective. Thus, further research is required with wider audiences to understand the implications of this work for science education (Gilbert, Boulter, & Rutherford, 1998). Our focus on the content of explanations made by seven participants who are research scientists is only the first step for a larger study to examine how the MACH model might inform learning in biology classrooms.

Thematic analysis also has limitations, one of which is overlooking individual differences. We attempted to analyze some of the deviant instances, but further qualitative research on mechanistic explanations would be fruitful to explore all the possible flavors of explanation, including those that occur rarely. However, the semi-structured interview process used here could easily be adapted to study variation among biologists. Furthermore, thematic analysis would not be the best way to find out how the MACH model relates to other models of scientific explanations commonly used in education (Braaten & Windschitl, 2011). As such, future research could focus on testing and clarifying other models of explanation by modeling and interviewing experts who use such explanations. First, some explanations follow a law-oriented

model, as summarized by Braaten and Windschitl (2011), which explains by deduction and appealing to predictable patterns, such as the laws of nature. For instance, Mendel explained patterns for inheritance of traits with his Laws long before much was known about meiosis. Second, a statistical model of probable factors that predict observable phenomenon under specific conditions is a model used in education according to Braaten and Windschitl (2011). For example, epidemiologists explain how factors, such as the frequency of smoking, can affect the likelihood of an outcome, such as a cancer diagnosis. As a third model of explanations, some scientists strive for a unification model that can address the maximal number of observable facts. It is difficult to imagine a unified theory of explanations, but when an electrophysiologist links the opening probability of a channel at a particular voltage to the measured membrane potential and action potential response in a neuron, the electrophysiology explanation is connecting otherwise disconnected phenomena in a way that is analogous to Maxwell's work that unified electricity and magnetism to address observations spanning many spatial scales. Future research would benefit from testing these models with interviews to account for how scientists in the biology disciplines explain. In so doing, researchers may adopt the methodology presented here to develop new models for other types of scientific explanations or in other fields.

Finally, as with all models, the MACH Venn model has limitations. Its purpose is to represent how the component themes interact to create coherent explanations. It does not represent, nor is it intended to represent, a process model that would try to indicate the sequence of usage of each component over time. Indeed, there is probably no single logical sequence to including the model components in an explanation. This will depend upon the individual and their interests and explanatory style. Another limitation of MACH model is that on its own it does not delve deeply into the specifics of the MACH components that are active areas of science education research. For example, some have argued that use of every language and analogies as distinct from scientific explanations should be considered when designing pedagogical tools to help students relate science to more informal ways of communication (1999). Others have

explored the importance of context for learning in biology (Watkins & Elby, 2013). Whether or not MACH helps educators to integrate such different research findings into classroom practice remains to be determined.

2.5.2 Implications

We hope that the outcomes of this research will be instrumental in realizing the recommendations from *Vision and Change* (Brewer & Smith, 2011), that is to say, to engage students in formulating and evaluating explanations in a way that is congruent with the practices of scientists.

Future research will focus on exploring the potential usefulness of the MACH model for educators. In this regard, for a previous published model (Schönborn & Anderson, 2009), a range of useful applications was subsequently published (Anderson et al., 2013), which we believe could also be useful applications for our MACH model. For the practitioner, these could include using the model to guide (1) the design of assessments that require mechanistic explanation, (2) the development of rubrics to assess student answers, (3) the identification of student competencies, deficiencies, and difficulties in certain aspects of mechanistic explanation, and (4) the design of class activities and instructional strategies to address such difficulties to teach students about mechanistic explanations. We have begun to use the MACH model in an education setting. However, factors such as the explainer, the audience, the content, the educational context, and the culture should be considered before transitioning the MACH model into a classroom setting (Gilbert et al., 1998; Treagust & Harrison, 1999). Instructional activities and a modified MACH model can be found at the Purdue International Biology Education Research Group (PIBERG) ePubs collection (Trujillo, Anderson, & Pelaez, 2014b, 2014a).

Towards the above goals, we have summarized the many observations of this research into a convenient set of guidelines that scaffold the important elements used in a biological explanation (Table 2.4). These guidelines repeat each of the essential

Table 2.4.
Possible guidelines for transitioning explanations about molecular and cellular mechanisms with the MACH model components into the classroom.

Is your explanation robust? Does it	
M.	Consider the tools and data used to generate and evaluate the explanation – *Methods*?
A.1.	Make use of appropriate analogies and models – *Analogy*?
A.2.	Tell a story as a narration that makes sense and relates to a purpose – *Story*?
C.1.	Identify a context for the mechanism in terms of organisms or cell types where it can be fully applied and understood – *Context of Biology*?
C.2.	Relate the mechanism to personal or social concerns – *Context of Society*?
H.1.	Consider entities, their interactions, and their states or variable properties – *How of Entities*?
H.2.	Include changing states of entities to produce activities – *How of Activities*?
H.3.	Translate vertically to consider several levels of biological organization – *How of Organization*?
H.4.	Translate horizontally to consider spatial and temporal changes – *How of Organization*?

components that were contained in our biologists' most well investigated systems so that a complete explanation can be provided. Along with the model, we hope that these guidelines can be used in a variety of ways to benefit instructors, students, scientists, authors, bloggers, journalists, and education researcher. We believe this can be helpful for a variety of tasks including structuring lectures, student self-study (M. Chi, De Leeuw, Chiu, & Lavancher, 1994), student peer instruction (Mazur, 1997), communicating with the public, writing and reading textbook or news explanations, assessing student explanations, and providing a theoretical foundation for future work in learning research. The MACH model provides a fresh lens to reinterpret the documented difficulties faced by students. For instance, an explanation indicating a difficulty with transcending levels of organization (Duncan & Reiser, 2007; Lewis & Kattmann, 2004) would correspond to the H component. Inappropriate connections to a visual representation (Schönborn & Anderson, 2009) would correspond to the A component. Indeed our confidence in the MACH model's use-

fulness for analyzing textbook explanations was reinforced when we returned to the textbook explanation of the signaling cascade presented in Molecular Cell Biology (Lodish et al., 2000) with our new model in mind to find that it not only met the requirements of the initial model but also all components of our final MACH model.

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CHAPTER 3. RESEARCH TO PRACTICE: HELPING UNDERGRADUATE STUDENTS EXPLAIN MOLECULAR AND CELLULAR MECHANISMS WITH THE MACH MODEL

Authors: Caleb M. Trujillo, Trevor R. Anderson, and Nancy J. Pelaez

> What, then, is time? If no one asks of me, I know; if I wish to explain to him who asks, I know not.
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>
> *Saint Augustine*

Creating explanations of cellular and molecular mechanisms is a key skill of practicing biologists that is often difficult for students to master. Despite this, only limited educational research has been published in this area and this has focused primarily on primary and secondary education rather than undergraduate education. Towards addressing this gap in our knowledge, in a previous study, we developed the MACH model of how expert biologists explain such mechanisms by focusing on four components, namely: *Methods, Analogies, Context*, and *How*, The goal of this study was to investigate whether the MACH model could, in turn, be usefully applied to improving the teaching and learning of this skill in undergraduate biology classrooms. More specifically, we addressed the following research questions: How does using the MACH model change the explanations written by life science students? For what reasons do students find it useful, if at all? To address these questions we enacted a teaching intervention in an undergraduate introductory biology using the MACH model as a heuristic to help life science students improve their explanations of molecular and cellular mechanisms. A mixed methods approach was used to collect written explanations before and after the intervention and to conduct interviews with a sample of student. Content analysis of explanations revealed that before the inter-

vention most students used three components naturally, but few included the research *Methods*. However, after the intervention students competently used all the MACH components. Inductive analysis of interviews indicated that the MACH model helped students to monitor their understanding, communicate completely and concisely, and identify gaps in their explanation. However, some students struggled to integrate the components as an expert would. The MACH model has potential to support education of scientific explanations but further research will be required to more fully understand the nature and quality of the explanations corresponding to each MACH component and how well they are integrated into a cohesive and grammatically sound whole.

3.1 Introduction

Anyone who has attempted to teach the detailed mechanism of transcription or DNA replication knows the difficulty associated with explaining the molecular and cellular world, yet as van Mil, Boerwinkel, & Waarlo (2013) have pointed out, a quick glace at review articles of molecular and cellular biology will reveal the central role of mechanisms. Therefore, it is important to understand the nature of explanations of molecular and cellular mechanisms and help students understand what biologists include when explaining such systems so that they may develop profeciency in biology. In 2011, biology and biology education leaders reached a consensus regarding competencies to address to improve undergraduate biology courses in a report entitled, *Vision and Change in Undergraduate Biology Education* (Brewer & Smith, 2011). One of the goals in this publication was to help students develop an ability to generate and evaluate explanations. Since experts develop such domain-specific expertise from many years of deliberate practice, novices need to do likewise in order to move along a continuum towards becoming an expert (Donovan, Bransford, & Pellegrino, 2000; Ericsson & Charness, 1994).

Thus the role of an educator is to guide students towards practicing relevant disciplinary skills. In this paper, we address a domain-specific skill practiced by biologists – the ability to explain biological mechanisms and investigate how introductory biology students progress towards mastery of this skill. When practicing biologists, who have reached mastery in their domain, explain, they may address questions about *why* or *how* a given phenomenon occurs. The former is explained by a theory-based ultimate cause (e.g. theory of evolution), while the latter is often explained by mechanisms (Mayr, 2004). In this paper, we focus on the latter, the how of biology – explanations about mechanisms that address how a biological phenomenon works.

While explaining is an indispensable skill, previous research results suggest that students face difficulties when explaining biological mechanisms. For instance, several studies note that secondary students struggle to address multiple levels of biological organization (e.g. going from molecular to macroscopic levels) when explaining biological processes (Bahar, Johnstone, & Hansell, 1999; Marbach-Ad & Stavy, 2000; Duncan & Reiser, 2007). Similarly, when explaining genetics, 10th grade students overlook the role of proteins (a type of entity) in their biological explanations (Duncan & Reiser, 2007). Furthermore, across many age groups, students avoid providing mechanistic explanations when explaining how biological phenomena occur and instead resort to ultimate causes (explain 'why') (Abrams & Southerland, 2001).

Another difficulty that could influence biology learning is the observation that explanations are susceptible to a type of memory illusion. Illusions occur anytime a factor biases an individual's perception about one's memory so that the individual overestimates or underestimates their performance compared to their actual performance (Roediger III, 1996). Typically, memory illusions are attributed to a mismatch between memory and meta-memory, sometimes referred to as meta-cognition. Meta-memory is defined as "the judgments, assessments, or commentaries that are made about memories or learning" (Dunlosky & Metcalfe, 2008). Explanations are susceptible to a type of memory illusion known as the illusion of explanatory depth. An illusion of explanatory depth occurs when "people feel they understand the world

with far greater detail, coherence, and depth than they really do" (Rozenblit & Keil, 2002). Through a series of studies, it was revealed that subjects tend to overestimate how well they can explain natural phenomena, but could more accurately judge their knowledge of facts, procedures, and narratives (Rozenblit & Keil, 2002).

In light of these known difficulties, our research goal was to propose an intervention to improve the explanatory abilities of students so that the students may overcome the above difficulties and learn to competently explain the discipline-specific knowledge of molecular and cellular mechanisms in biology. Towards this goal we deployed the MACH model of Trujillo, Anderson, and Pelaez (in press), in a teaching intervention to address student explanations of biological mechanisms.

3.1.1 The MACH model

The MACH model is a representation of the components included by biologists when they explain biological mechanisms – the *how* of biology . Trujillo et al. (in press) interviewed practicing biologists and identified four themes present in their explanations. This data and subsequent analysis informed the development of the MACH model. The model has four components. Biologists include *Methods* (M), *Analogies* (A), *Context* (C), and *How* (H) components when explaining their familiar mechanisms (detailed below).

The *Methods* component includes references to the research tools, data, and procedures used to understand a given mechanism. Biologists discuss research methods when they explain how scientists know about a mechanism. As a second component, they incorporate *Analogies* including visual analogies like models and diagrams, anthropomorphize entities, and use metaphors to connect mechanisms to everyday experiences. The *Context* component includes biological and social context. Biologists embed their explanations in a social setting such as disease when explaining, as well as, contextualizing around the organism, taxon, cell-type, or other biological settings in which the mechanism takes place. In addition to the M, A, and C, biol-

ogists focus heavily on H, *How* the mechanism works. H is the traditional view of a strictly mechanistic explanation. With the H component, biologists describe "how the component entities of a biological phenomenon interact at the molecular, microscopic, and macroscopic levels to produce detectable changes in state, activities, and organization in space and over time." (Trujillo et al., in press) For example, the H component of explanation of receptor tyrosine kinase (RTK) pathway describes entities such as ligands, receptors, and proteins and their changing states. States are variable properties of the entities such as specific chemical modifications or conformations of biomolecules. States can be general such as active and inactive forms. The interaction of the entities (e.g. ligand-receptor) cause changes in the states, which is to say, they produce activities. For instance, once the ligand is bound (interaction), the receptor dimerizes (state) and cross-phosphorylates residues on the other dimer (activity). Entities and activities are organized over time and space. Thus, they change the biological system in a sequenced and localized manner. This in turn can change the state of the whole cell and tissues i.e. these changes transcend levels of organization. The appropriate combination of the entities, activities, and their organization achieves the *How* component when explaining a given biological phenomenon. Each of the MACH components can be used as constructs for components of a biological explanation.

Biologists integrate the four MACH components together to create complete explanations about mechanisms using domain-specific knowledge from their extended experience and understanding. Taken together, the MACH model represents the components practicing biologists included when they explain biological mechanism. MACH offers a model to guide how learners explain causal mechanisms in biology. (Trujillo et al., in press)

3.1.2 Rationale and research questions

Given that students face difficulties when explaining in biology, and that the MACH model represents which components biologists use to explain mechanisms, we identified an opportunity to use the model in an intervention to improve students' explanatory skills to do with molecular and cellular mechanisms in biology. In so doing, we were interested in the nature of any change in student explanations that occurred and to what extent students thought that the model supported their learning. Therefore, this study addresses the following research questions:

1. How does using the MACH model change the explanations written by life science students?

2. Why do students think learning about the MACH model is useful, if at all?

Research Question 1 is focused on how students change the way they explain biological mechanisms following a teaching intervention. As guiding questions, we asked how many students were using each of the MACH components before the intervention and after the intervention, and did a significant number of students change their use of such components? In addition to the analysis of student explanations as a measure of change, it was important to understand why students change after practice with the MACH model, and to identify any other outcomes from the intervention. Research Question 2 is focused on the types of successes and challenges students face that may not be captured by the measures of their explanations. To address Research Question 2, we sought to understand: Do different students find that learning the MACH model is useful? If so, for what reasons do they think learning it is useful? In order to learn how to minimize harm and detriment, and to build on strengths of the MACH model improving explanations of all students, we conducted interviews to explore how and why the MACH model influenced students' abilities to explain.

3.2 Methods

A mixed-methods study was conducted to explore the effectiveness of a teaching intervention. The intervention was designed to improve undergraduate biology students' domain-specific knowledge and the quality of their explanations. The MACH components, Methods, Analogies, Context, and How, operated as constructs that represented the components that experts use to explain in biology. A mixed methods approach was chosen because it allows several types of data sources and methods (e.g. analyzing written explanations and in-depth interviews) to be used in a complementary fashion and because the research takes place in a real-life context (Creswell, Klassen, Plano Clark, & Smith, 2011). The methodology places priority on quantitative analysis supported by an embedded qualitative approach.

3.2.1 Student population

Research was conducted in a classroom setting of a large Midwestern university in the United States. The course, in which the teaching intervention occurred was implemented, was the second of four lower division courses in introductory biology. The fifty-six students enrolled were primarily freshmen and sophomores. In addition to the written explanations collected from the course, four students were recruited for in-depth interviews and analysis of explanations. All data were collected under the approval of the Institutional Review Boards (protocol numbers 1306013717 & 1203012039).

3.2.2 Design of the intervention

The purpose of the teaching intervention was to aid students to structure their explanations according to the MACH components and to guide their learning and construction of explanations about biological mechanisms. Towards this end, a teaching intervention was planned and implemented using a modified version of the

MACH model. The modification entailed developing a paper-based physical model in the form of a fold-out tetrahedron in which each vertex of the tetrahedron represents a different MACH component. This tetrahedral model is available online (Trujillo, Anderson, & Pelaez, 2014b, 2014a).

At the start of the intervention, the students were assigned in-class worksheets and problem sets (Supplement) and told to work individually. During the intervention, students received a 50-minute guest lecture from the first author.The goals of the lecture were to help students practice using the MACH Model to develop an ability to evaluate their knowledge of explanations, to analyze an explanation and a video, and to construct an explanation. The lecture was incorporated on the topic of neurons and action potentials and focused on topic of vesicle trafficking. The lecture followed four steps. First, students watched a molecular animation of vesicle trafficking (Liebler, 2007). Second, students wrote their own explanation about how vesicles traffic. Third, the students were instructed about each of the MACH components using examples from the assigned reading. Finally, students folded the tetrahedral model and were instructed that a complete explanation would connect all four vertices. Throughout each step, students followed a worksheet and evaluated their knowledge about vesicle trafficking by answering clicker questions.

Along with the intervention, students completed a problem set to practice identifying the MACH components in a summary about a 2013 Nobel Prize (Zierath & Lendahl, 2013) and in a review article about vesicle trafficking (Bonifacino & Glick, 2004). After analyzing the articles, students created their own written explanations of these topics. Altogether, the students were given many opportunities to use the MACH model since several later course assessments about molecular and cellular mechanisms also required students to write explanations specifically informed by the MACH model.

3.2.3 Evaluating student explanations

Data collection

Explanations were collected at multiple time points including before and after the intervention (Figure 3.1). Before the intervention, students completed an explanation on exam two. The exam two prompt read:

> Choose any ONE specific example of a protein conformational change that plays an important role in the regulation (control) of a response to light by a plant cell. Write a maximum 1-page essay to explain the mechanism of your selected process. Draw and label a diagram as part of your explanation. Describe all the details you know about the phenomenon.

After the intervention and initial problem set, students were asked to create an explanation on exam three. They further practiced using the MACH model by researching a topic of their choice, collecting original research articles, and presenting a poster individually or in a small group. Finally as part of their fourth exam (final), students were asked:

> Choose any ONE specific example of a mechanism that you learned about this semester. Write a maximum 1-page essay to explain the mechanism of your selected process. Draw and label a diagram as part of your explanation. Describe all the details you know about the phenomenon. Use the MACH Model, presented in class by Caleb Trujillo, to guide and structure the content of your explanation. Make it clear which parts of your explanation correspond to each component of the model.

All exam prompts were available one week in advance. Apart from the research presented, these prompts were used to evaluate students' course performance, and as such, teaching staff graded student responses for correctness in a manner that differed from the analysis presented below. All relevant prompts of exams and other

data sources can be found in the supplement materials (Supplemental Table 3.5, page 100).

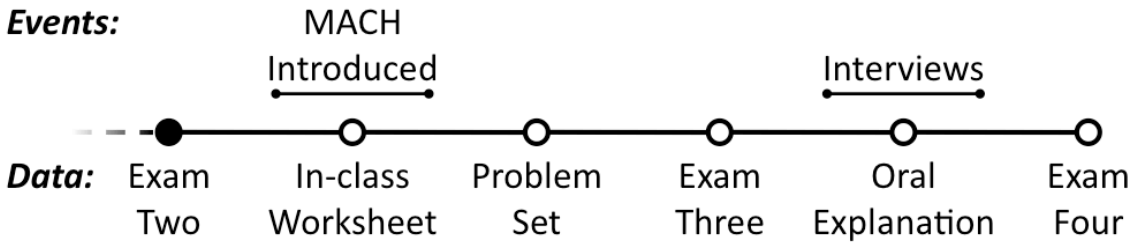

Fig. 3.1. Timeline portraying events and data collection of explanations. Filled circles represent data collected before the intervention; unfilled circles represent explanations during and after the intervention.

To answer Research Question 1, the frequency of students using each of the MACH components was measured before and after learning the MACH model. In order to evaluate the change, we examined explanations produced in exam two and exam four as representations of student's explanations before and after the intervention.

Data sampling

Data was stratified based on the final course grade of students and then sampled to ensure that we would examine findings for students at variable achievement levels. We used *ex post* course letter grades to stratify students into four performance groups: students who received the highest grade possible (n=5), an A (n=7), a B (n=7), and a C (n=6). By stratifying the student response, we intended to gain an estimate of how students of varied performance in the course were explaining before and after the intervention. The highest-grade and C groups have smaller samples be-

cause all students of each respective group were included. Within these grade groups, each student's exam two explanation was paired to his or her exam four explanations. D, F, and W groups were excluded due to lack of attendance and missing assignments.

Data analysis

Content analysis was performed on the student explanations from exam two and exam four for each student in the sample. This was done by two raters (first and third author) to ensure inter-rater reliability. The coding guide (Table 3.1) was based on the operational definitions of the MACH model (Trujillo et al., in press). The explanation would be marked "present" for the M component, if and only if the explanation contained any of the following: Tools, Procedures, or Data. Otherwise, it would be marked "absent." Once the selected responses were coded using the coding guide, the proportion of students with each of the MACH components was calculated and expressed as a percentage. To determine whether or not there were detectable changes in the prevalence of components before and after the intervention, McNemar's Exact test (Fay, 2010) was performed with the null hypothesis that the relative frequency of students using each component did not differ between exam two and four (Supplement). The test was performed with R statistical package using command "mcnemar.exact (x)".

Table 3.1.: The codes of the MACH components (from Trujillo et al., in press).

MACH Components *Descriptions with Examples*
Methods: The *tools, data,* or *procedures* used to generate evidence that informs the explanation and qualifies or limits the generalizability of interpretations. *Procedures* include protocols or processes such as experimental design and transgenic comparison. *Tools* include instruments used to observe, visualize, and record evidence such as X-ray crystallography, devices, microscopes, and oscilloscope. *Data* refers to quantitative measurements, variable properties, observations, and physical properties of the system, such as biomolecules and cellular environment, as well as, the findings from experiments[1].
Analogy: The stories and analogies that make sense of and relate to a purpose for the mechanism with *formal analogies, models,* or *narrative forms*. *Formal analogies* are explicit analogies to represent a similar function or property, metaphor, or simile and are evident by language such as "An ion channel behaves like a door to a room" and Lock-and-keys. *Narrative forms* are informal ways of explaining that include: story telling; Teleology; reverse causality; need-based, environmentally deterministic, and purposed formulations; and forms that attribute human or animal characteristics to non-animal entities (anthropomorphizing). These non-causal statements attribute molecules with an experience that goes beyond collisions, binding, and interactions, such as, "The cell runs out of energy", hyperactive, and signals. *Models* are visual (non-textual) representation of the explanations, such as, representations, diagrams, graphs, mathematical models, chemical formulas, etc.
Context: The *biological context* or *social concerns*, which connect the explanation to a setting where it can be fully applied and understood. *Biological contexts* are established biological relationship by distinguishing organelle, cell type, organ, etc, or connecting to evolutionary history. *Social contexts* depict a human or societal concern and examples include disease, health, or other social issue.

Continued on next page

[1]We do not include implications.

MACH Components *(Continued)*
Descriptions with Examples

How: A description of how the component *entities* of a biological phenomenon *interact at the molecular, microscopic, and macroscopic levels* to produce detectable changes in *state, activities,* and *organization in space and over time.*

Entities are the living and physical components of the system such as biomolecules, proteins, organelles, cells, etc. and these entities interact by binding and inhibiting and have states. *States* are in the form of modifications, isoforms, or specific confirmations, such as open confirmation, phosphorylated, hyperpolarized, and bound states. When these states change, *activities* occur; enzymes activate from 'off' to 'on' or proteins becomes phosphorylated. Entities and activities exist at several *levels of biological organization.* They are organized by timing and order, which are depicted by rate, frequency, sequence, causal chains ("X induces Y"), etc.[2] The spatial arrangement of entities and activities also maters such as localization, "inside the cell," structure, orientation, connectivity, compartmentalization, distance, and conformation.

To account for reliability, two raters, the first and third authors, coded a sub-set of responses, revised the codes according to disagreements, and repeated until greater than 95% agreement was reached. An estimate of inter-rater reliability was made for each of the components by comparing responses between raters using Cohen's Kappa (Supplement). With Cohen's Kappa, the degree to which raters agreed could be compared to the degree expected by chance agreement; this allows for an estimate of reliability (Stemler, 2001).

3.2.4 Student interviews

To answer Research Question 2 and understand why and how students thought the MACH model was useful, if at all, four students of different levels of performance were interviewed about how they experienced and used the MACH model throughout the semester.

[2]We do not include sequence implied in the visual model (i.e. arrows), or concentration dependent mechanisms.

Table 3.2.
Biographical information of the student interviewees.

Participant (Pseudonym)	**Performance exam three explanation**	**Sex**	**Major**	**Class**	**Research experience**
May	Below median	Female	Biology	Freshmen	None
Felix	Below median	Male	Plant science	Freshmen	>450 hours
Petunia	Above median	Female	Pre-pharmacy	Freshmen	None
Capt. America	Above median	Male	Biology	Freshmen	None

Data collection

Two students who performed well using the MACH model and two who faced difficulties were recruited for interviews. Their performance was inferred by their score on a single explanation from exam three (Table 3.2). These students were selected to understand how students of varying success used the MACH model and whether thought it was useful. Each pair contained a male and a female. Interviews were semi-structured around four parts: background information, oral explanation of a mechanism of choice, discussion of experience with the MACH model, and debriefing by reflection on student-made artifacts. All the artifacts from these four students, including written and oral forms, were evaluated for the presence of MACH components using the coding guide. These artifacts included an explanation from exam two before the intervention, an explanation from the in-class worksheet during the intervention, two explanations from problem sets after the intervention, one oral explanation from the interview, explanations from exam three and exam four (one each) after the intervention.

Data analysis

Audio recordings from the student interviews were transcribed. The transcripts and artifacts were analyzed using inductive analysis (Lincoln & Guba, 1985) to understand each student as an individual case. Additionally, crosscutting constructs were organized around the data, and were systematically related across the participants when possible. If a particular construct was well supported across interviews by its prevalence and its degree of support, it was identified. Once several constructs were identified, assertions drawn from the analysis were strength tested. This was done by organizing supporting and disconfirming evidence (in the form of quotes and artifacts) and weighing the prevalence and strength of the evidence in regards to an assertion. By analyzing these four students' use of the MACH components throughout the semester and by interviewing them to understand their experiences with, and their reflections about the MACH model and the intervention, we hoped to better understand why a student would change the way they explain after the intervention. Once results were written, member checking was performed with one student by going through a complete draft of this document.

3.3 Results

From the data, we were able to address the research questions in an objective manner. Two raters were able to code the data, and inter-rater reliability was measured to be greater than 95 percent agreement for all components after one round of rubric revision (20 responses). Due to the homogeneous coding of the A and H components, Cohen's Kappa could only be found for M and C. Both M and C resulted in a κ of 1. Complete coding by the first author using the coding guide was used to report findings (Supplemental Table 3.6, page 101).

3.3.1 How student explanations changed

Regardless of grade band, most students used *Analogies*, *Context*, and *How* components before learning MACH, but lacked *Methods*. However, the proportion of student who incorporated the M component into their explanations increased after the intervention (Figure 3.2). Analysis of the exam two explanations revealed that most student explanations contained *Analogies*, *Context*, and *How* components before the intervention, but few (32 percent of the students) included *Methods*. After the intervention, students maintained the high use of A, C, and H, and the proportion of students who use M increased to 92 percent. The inference that the frequency of inclusion of the M component in student explanations changed significantly was supported by the McNemar's exact test (Rejected null hypothesis, $P < 0.0001$) and by a 95% confidence interval from odds ratio that surpassed 1 (3.587, Infinity).

3.3.2 Why students thought learning the MACH model was useful

For the purposes of reporting the findings in a concise manner, two of the four interviewed students' cases are presented in rich detail. The two students are Felix, a student who struggled with using the MACH components in his explanations, and Petunia, a student who was able to incorporate the components immediately. Analysis of students' explanations across many data sources (Table 3.3) and interview data revealed patterns that were found across all four participants. Many expressed similar views to Felix and Petunia. Table 3.4 indicates the prevalence and strength of assertions that were found through our analysis of the student interviews and explanations relevant to why the model affected students. Examples of each of the claims can be seen in the cases presented below. All four students reported that the model helped them self-monitor their understanding, communicate completely and concisely, and identify gaps in their understanding.

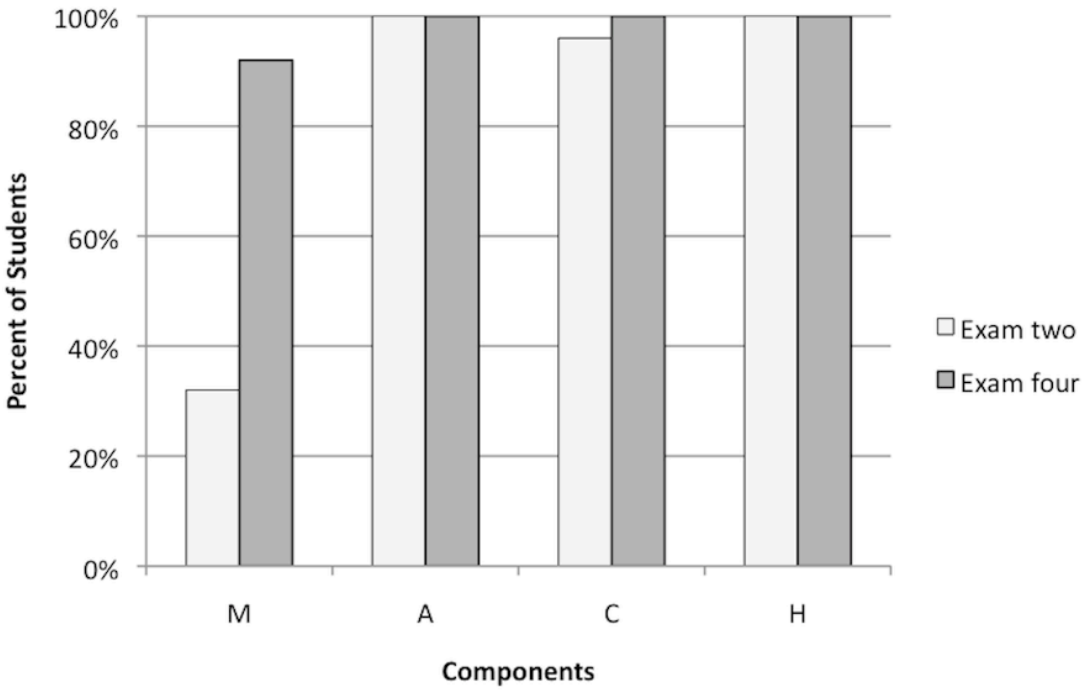

Fig. 3.2. Presence of MACH components in student explanations for exam two and four.

Table 3.3.
MACH components incorporated by Felix and Petunia into explanations of various mechanisms, in response to a range of assessments given to students during an introductory biology course, before, during and after an intervention.

Source	**Felix**		**Petunia**	
	Mechanism	***Components***	***Mechanism***	***Components***
Before intervention				
Exam two	Phototropism	MACH	Activation of phytochrome	ACH
During intervention				
In-class worksheet	Vesicle trafficking	AH	Vesicle trafficking	H
After intervention				
Problem set A	Vesicle trafficking	MACH	Vesicle trafficking	MACH
Problem set B	Regulation of guard cell	ACH	Related to thalidomide	MACH
Exam three	Phototransduction	ACH	Phototransduction	MACH
Oral explanation	Regulation of guard cell	MACH	Related to thalidomide	MACH
Exam four	Mechanism of apoptosis	MACH	Related to thalidomide	MACH

Table 3.4.
Frequency and strength of various claims made by students during interviews about the perceived effect the MACH Model had on their ability to explain mechanisms. '+++' indicates extensive evidence; '++' substantial evidence; '-' some disconfirming evidence. 4 students.

Claim	***% prevalence & strength***
Students practiced self-monitoring to reach a deeper level of understanding when they used the MACH model.	100%, +++
Students communicated complete and concise explanations when using the MACH model.	100%, +++/-
Students recognized gaps in their understanding when using the MACH model.	100%, ++

3.3.3 The case of Felix

Felix was selected for interview due to his poor explanation created in exam three. His explanation scored below the median after the teaching intervention and practice with MACH. We chose Felix to understand why a student who faced challenges when asked to explain with MACH would change the content of his explanation after practice using the MACH model. Felix had extensive research experience compared to most students his level. From our analysis, Felix, similar to his peers, struggled with particular components. From his written work and interview, the growth in his explanation was evident. He went beyond checking boxes, towards monitoring his own understanding. Additionally, Felix provided insights about how to improve teaching and learning with MACH.

Background

Felix's family had lived in the area for nine years before he attended university. He was a freshman majoring in plant sciences, and he took the biology course in case he later changes his major to biology. While he had always been a good student,

he felt the other students in this class were ahead of him academically. He was a B-student, competent and hard working. What made Felix a unique student was his experience doing research in two different plant research laboratories over three summers.

Initial difficulties

Felix viewed the MACH model as a deeper version of everyday explanation. He stated:

> The main difference between the MACH model and just normally explaining is the Methods and How, how the mechanisms works, and how people found how the mechanism works, and that requires and little more in-depth than you normally would with anything else. (Felix 2: 138-141)

He was aware that using the MACH combines parts he felt he was using like Analogies and Context. However, Felix initially did not include the Methods, Context, and the details of How in his explanations. For example, during the initial in-class explanation of vesicle trafficking he wrote:

> When mRNA is brought into the cell, the proteins are synthesized and packaged using endoplasmic reticulum. The packages are then carried as a group in a vesicle, which is made in the Golgi Apparatus, by a motor protein. The motor protein follows microtubules to bring the vesicle to the cell membrane, where the vesicle fuses with the membrane and releases its contents. (Felix, In-class explanation)

This explanation included the *How* component. Felix referred to entities such as mRNA, proteins, organelles and activities of these entities such as packaging, carrying, and fusing. Additionally, he considered the organization of the mechanism by naming locations such as the cell membrane, distinguishing compartments, and giving a temporal sequence. It was completely devoid of both *Context* and *Methods*.

For instance, the mechanism made no reference to how vesicle trafficking relates to a biological setting such as neuronal signaling or to a social concern such as diabetes. Likewise, the explanation made no indication of how researchers learned about such a mechanism; data, methods, and procedures are absent. In addition to Felix's writing, he included a model of the mechanism, a type of *Analogy*, and he used language to treat the motor protein as an actor with a purpose. When shown his explanation, Felix agreed, "It is only talking about the molecular level and not everything is explained clearly like how motor proteins are used or how the vesicle is formed. [. . .] This is kind of an inadequate explanation." (Felix 2: 442-445) Felix found *Methods* and *Context* to be a challenge. This was also noted in his explanation from exam two about phototropism. Felix's exam two explanation had all MACH components, but the *Context* and *Methods* components were rather superficial. Both the exam two and in-class explanations indicated that Felix needed to improve his use of the M and C components, as well as the quality of H component. These identified struggles were further supported by the interview data.

During the interview, Felix was open about the difficulties he faced when using the M component. For instance, related to the preparation for his group poster about an article related to cancer, he stated the following:

> Yeah, definitely *Methods* were the hardest part. And I feel like that was a big thing when you introduced us to the MACH model was, like, *Analogies* were very easy. You know you could find a graph or talk about it in a different perspective. The *Context* was fairly easy to do as long as you knew what the research, cause you know in order to conduct research you have to have a context. I think *Methods* were the hardest parts especially when we started out because we just weren't given that. (Felix 2: 81-87)

Felix found that *Analogies* and *Context* came quite naturally for him in his explanations but understanding the *Methods* was difficult. During exam three and after the intervention, Felix explained how a photoreceptor responds to light (Figure 3.3) when he wrote the following:

> Rhodopsin is an important photoreceptor that, along with the other opsins, has allowed humans and other organisms create visual images. This multi-step response to light begins with a protein being absorbed by rhodopsin, after which a heterotrimeric a-protein called transducin is catalyzed. When transducin is catalyzed, cGMP-specific phosphodiesterase, or PDE, is activated. PDE 'eats' up cGMP, which are normally bound to Na^+ channels to keep them open. Therefore, cGMP levels are low in the presense of light, but return to higher levels in the dark, as shown in [Figure 3.3A]. This cascade of events in a network of photoreceptors leads to the creation of an image. When light is not focused on the central point, however, lateral connections inhibit the maximum potential of an eye to see. How the cascade works is show in [Figure 3.3B]. (Felix, Exam three)

Felix indicated cGMP levels (M, according to our coding rubric), but this representation was not thorough (Figure 3.3A). Felix acknowledged this when shown his explanation:

> I don't think I did too well on this. [. . .] I talk about how photoreceptors work and how it relates to certain secondary messengers, and alot of this is just *How*. Actually, all of this is how it works and almost none of it is *Methods*. There is a little bit of *Context*, and there is like no *Methods* in this at all, which is kind of like what I was talking about with the class and not having been taught how certain things were found. (Felix 2: 459-466)

Felix affirmed that the *Methods* are a weaker portion of the explanation, but he also felt as though the instructor did not spend enough time explaining how scientists resolved the phototransduction mechanism. He stated:

> Like we would talk about, for instance, opsin and light receptors and mammalian eyes and we would know how they worked but we weren't

> given any information about like how people found out it worked that way. [. . .] Alot of people [students] I feel like struggled [on the exam] trying to get the *Methods* because all we reviewed was stuff in the lecture and from the book and there wasn't too much of the *Methods* in that, but once we got to independent research parts [the poster] where you look up papers and stuff. You know it was alot easier to find the *Methods* that way because they list it out for you. (Felix 2: 89-98)

As a student, he observed that the expectations of the assessment to include components (e.g. *Methods*) were in discord with what he thought was covered in the learning material and lectures. However, *Methods* were presented during a lecture. In fact, Felix's drawing appeared similar to the research methods represented in lecture by a cartoon analogy. In this excerpt, Felix noted that he could not identify the *Methods* in class, but he could within the research articles. During his independent project, he recognized M in the research literature. Being unable to recognize or relate the *Methods* within lecture to the mechanisms he was learning affected his ability to use the MACH model during exam three.

Felix initially struggled with providing M, C, and detailed H, but the use of M was the most persistent challenge. Felix recognized that the *Methods* were difficult for him to include and his initial artifacts indicated this as a clear area for improvement. This difficulty can be attributed to his lack of knowledge of the *Methods* and his difficulty identifying it in lecture. However, by the end of the semester, Felix used all of the components.

Growth

Felix overcame the challenge of using all the MACH components. His problem set explanation and the explanation he later gave during the interview were easy to contrast since both addressed the regulatory mechanism the actions of stomatal guard

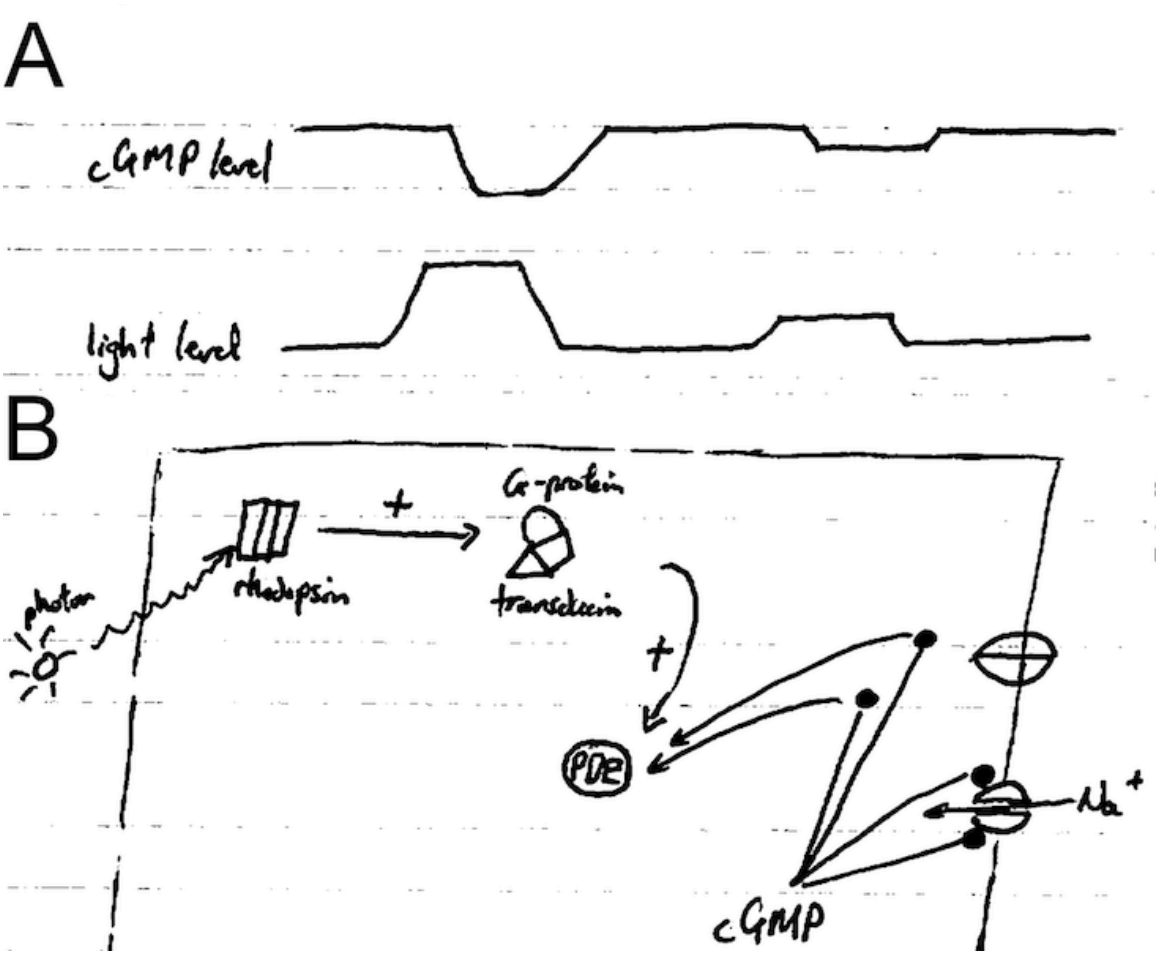

Fig. 3.3. Drawings by Felix of the mechanism of phototransduction. Panel A indicates the fluctuations of cGMP levels related to light exposure. Panel B indicates a diagram of the molecular mechanism.

cells. This mechanism was familiar to Felix due to his previous research experience. For his initial explanation after learning the MACH model, he wrote:

> Stomata are very important to the survival and maintenance of any plant. They regulate gas exchange and the concentration of water within the plant in relation to its surrounding environments. The opening and closing of the stomata is dependent on potassium ions flowing in and out of the guard cells surrounding the pore through ion channels. When the plant is under ideal conditions and ready for gas exchange, potassium ions will flow into the cell. Water follows K^+ ions, therefore, the influx of K^+ ions is followed closely by the increase of water in the guard cells. When turgid, the guard cells are pushed apart to open the pore. When the plant closes its stomata, the process is reversed, K^+ is channeled out of the cell and water follows it, causing the cell to be flaccid and closing the pore. This mechanism operates similarly to a set of water wings used by small children in pools. When air is pumped in, the wings inflate, widening the hole through which the child places his or her arms. After air is released, the wings deflate, closing the arm hole. (Felix, Problem set)

Felix contextualized the mechanism by introducing the importance for the survival of the plant and how it interacts with the environment. He gave the causal mechanism (H) and used an analogy of a water wing to communicate the actions of the stomata (A). However, there was no *Method* in this response, but during his oral interview, Felix used all of the MACH components for the same mechanism. For instance, he put the explanation into a *Context*, "We were looking at drought tolerance because plants lose up to 90 percent of their water when they are open which is a really big problem because if you are trying to grow plants in a desert." (Felix 2: 304-307) He was able to connect his mechanisms to the social context of agriculture. Along with this context, his oral explanation contained *How* and an analogy identical to one used in the problem set.

> When a plant is undergoing stress from drought, it is going to release abscisic acid, which is a hormone that causes an increase, sorry a decrease in the amount of potassium of a stomatal guard cell, which causes water to flow out because water follows the potassium out of the cell, and once the water flows out of the cell, the guard cell shrinks and becomes flaccid and that is what closes the stomata. It is kinda like a water wing that kids use in pools. [. . .] Obviously a plant needs to be able to exchange gases with the environment it needs to be able to take in CO2 and release oxygen and the only way it can do that is through stomata. And it is really important that it can be able to open and close it at will because one of the drawbacks of having basically a hole in your body is that you are going to be losing water and plants need water to survive and when they transpire, every minute they have their stomata open they are losing water and that is kind of trade off that plants have to figure out. (Felix 1: 268- 290)

Felix referred to entities, specific hormones, and ions, and their activity in the stomatal guard cell (the *How*). Additionally, he used *Analogies*, by anthropomorphizing the plant and using need-based formulations when he said, "it needs to be able to". Furthermore, Felix included *Methods*.

> So one of the things we looked at in our research was the density of stomata cells on a leaf and how it correlated with how well it uses water or its water-use efficiency. [. . .] I got to count all the cells by hand, which was terrible because just within a week I think I counted 29,000 some cells which included the stomata cells and the epithelia cells around it, and so I got to know stomatal density pretty well. (Felix 1: 310-329)

Felix was speaking from his experience in the laboratory and connecting the mechanism to how one goes about studying stomata cells. He used the MACH components in the way that biologists explain. Felix used the M to explain during his interview,

as well as on exam four, indicating his growth. Overall, the presence of the MACH components and the quality of each component increased.

Why Felix found the MACH model useful

While it was clear that Felix changed regarding the components he was including, the question remained as to why the teaching intervention had the observed effect. He states: "Understanding a topic more thoroughly is certainly the biggest thing that comes out of the MACH model because it forces you to figure these things out just like the *Methods*." (Felix 2: 332-334) For Felix, using the MACH model helped him learn the mechanism to be explained, since it made explicit what he should understand. It allowed him to focus specific parts of information that would improve his explanation. He made this point explicit:

> I feel like the MACH model requires alot more understanding of a topic than just explaining it to someone on the street. [...] We have to use this model on the homework and so as students we don't want to do as much work as teachers want because we have other classes and everything. So it was kind of annoying having to go through all these things and making sure I understood, like, at certain levels or I meet certain requirements of the MACH model before I could proceed with other questions in homework. But at the same time, if [...] that was the only thing I had to do for the entire day. I feel like it would be alot better in understanding [...] Instead of taking that just, you know, surface level understanding. I wonder how this works on a much smaller scale system. (Felix 2: 161-177)

Felix used the model to monitor his understanding. It forced him to go deeply into the material when studying. However, Felix pointed out that he felt annoyed and that he did not have enough time to explain at the level he wanted. The benefit of deepening understanding was not without drawbacks, as illustrated in the following conversation:

> Felix: I think that is one of the downsides of the model when you go deeper into it [...] the more you realize you don't understand as much as you think you do about a certain topic and I certainly had that experience with the cancer thing that we were doing for the poster. Like okay, I think I know how this works because it was talking about apoptosis and programmed cell death, and I'm like, oh yeah; I have heard about that plenty. So I kind of put that off but then once I started reading into it and how it works and everything I am like um you know this is a little over my head I don't know if I understand it. [...] I feel like you are more uncertain knowing that you don't know it than before when it was just at that single level [...] Just having to use it (MACH) over and over again I feel like would make me feel more comfortable with it.
>
> Interviewer: Okay, so what I am hearing is that by using it, it is actually revealing where those gaps are in your understanding [...] while it is good that you are going deep you are also realizing how little.
>
> Felix: Yeah, how little you know. Yeah, it is a little discomforting. [...] It's like the more I know, the more I realize that I don't know things, and that is kind of like really unsettling. [...] I don't know if that is a disadvantage of the MACH model or an advantage, you know, kind of motivating you to learn more, but certainly the first few times that I actually applied the MACH model I felt overwhelmed. (Felix 2: 207-249)

Felix recognized that once he read and applied the MACH model he did not know as much as he previously thought. Felix's account was consistent with the illusion of explanatory depth. He misjudged his level of knowledge based on familiarity. Discouragement and discomfort came as he reevaluated his knowledge, and this helped him learn more about the topic he was pursuing.

Recommendations

When asked how to improve the teaching intervention, Felix expressed that he would have preferred to learn how to use the MACH model earlier in the semester. He expressed:

> If this MACH model is going to be implemented into other courses I feel like it should be introduced in the beginning of the course that way we have it in our minds and that way we have more time to work with it. I feel like with alot of the exam questions, like the first and second exams, I feel like knowing the MACH model would have been beneficial to us and to providing better answers than what people did. [...] In my personal opinion, I feel it should be introduced to students early on saying you should start thinking about this and we are going to start doing some practice about this in a few days and just give them that entire semester's worth of practice. I feel like that would be alot more beneficial to the students than introducing it to the students half way through and trying to implement it because by then the first half of the semester we are using our own methods of explanation. (Felix 2: 525-541)

Felix pointed out that the MACH model took practice and that when left to his own technique he would explain things in his own way. His recommendations suggest that he found benefit in using the mechanism and would like instructors to make the model explicit early in the semester. This recommendation, if implemented, may also reduce the discomfort experienced when gaps in understanding are revealed using the MACH model since students could be gradually exposed to this model for explaining.

Summary of Felix

Felix's case complemented the quantitative measures. Initially, Felix faced difficulty using *Methods*, which paralleled the difficulties seen in the class as a whole.

Additionally, Felix was able to improve the quality of all of the MACH components to make thorough explanations after the intervention and with practice. Felix noted that using the MACH helped him to monitor his understanding and revealed gaps in his understanding, but this lead also to feelings of discomfort. This case helps us understand why the MACH model had an impact. The insights provided by Felix were echoed by others including Petunia.

3.3.4 The case of Petunia

We selected Petunia for an interview due to her high performance on her exam three explanations. She scored above the median. Petunia was among the top students in the class. We chose to discuss Petunia's data so as to represent what a student with high marks could gain from using the MACH model. She, like Felix, did not include all the components before the intervention, but she overcame this deficit quickly. Petunia's progress was centralized around being able to explain concisely and efficiently. For Petunia, the benefit of the MACH model was its use as a tool for communication. However, some parts of her interview were not consistent with her artifacts.

Background

Petunia was a freshman student who excelled in her coursework as a pre-pharmacy student. Growing up in a nearby developing metropolitan suburb, she had experienced many educational opportunities. For example, she had completed many Advance Placement courses before attending university. Although she lacked research experience as a freshman in college, she was considered to be a top student and a source of information by her peers.

Initial difficulties

Petunia was able to see many similarities between the tenets of the MACH model and her normal explanations. She noted:

> Initially, it was really exciting to me because of the commonalities. Wow, that is quantifying something that I have been doing for a long time and I never knew it. [...] I could see in this model the positive things about how I could explain something to a classmate and for them to understand, and saw in the model a couple of things I wanted to refine in my explanations. (Petunia 1: 455-461)

She, like Felix, found that the MACH model was consistent in many ways with how she explained in biology already. Petunia stated:

> My friends would always say oh you should be a teacher you are really good at explaining things. [. . .] I found it alot in common with the MACH model. The hardest part for me was like the analogies. Sometimes I feel like I have to force that, and the reason is because in my presentation I made an analogy about a vacuum cleaner, like I made myself say it. [. . .] But for me, like *Methods*, [. . .] that is like how I think. I need the background to know the conclusion; it wouldn't make sense unless I knew this is like how they figured it out. I won't just accept this is how it is. I say well why? That is something that I feel is important when I explain to other people because that helps me to understand and I know that. My friends have given me feedback, and again, context is really important. I spent like the first five minutes talking about the history and how that is what appealed to me and made it significant. I feel like for me when I explain, to me when you make it significant, it's memorable, it's valuable, and it's not just like memorize it for this test and forget all about it, and I mean *How* is the correct stuff like what you are trying to talk about. (Petunia 1: 238-260)

Petunia believed that *Analogies* were the hardest part of the components to use, and that using *Methods*, *Context*, and *How* was the natural way she explained. This was because she believed her normal explanation focused on how scientists figured out the mechanisms, and she included the importance and history of the mechanisms as part of the "correct stuff" of the mechanism. On the other hand, she had to be mindful to include *Analogies*. Surprisingly, analysis of her early work indicated that her reported difficulties were not consistent with those that were identified by our analysis.

Petunia's explanations lacked components she had claimed to use. Her exam two explanation indicated use of A, C, and H, but did not include M for her explanation of phytochromes of flowering plants. Likewise, when explaining how vesicles traffic, her in-class explanation was lacking. Petunia only included the H. During the in-class explanation she wrote the following:

> Vesicles can be formed through endocytosis of extracellular materials into the cell by infolding of the cell membrane. Vesicles are also created during the formation of cell protein as RNA codes for a protein sequence and this polypeptide is processed in the endoplasmic reticulum. Once proteins have been refined by the ER they go to the Golgi Apparatus where they are packaged into vesicles by expanding removing sections of membrane. These vesicles are transferred along all fibres that branch out from the centrioles by motor proteins. Meanwhile, vesicles formed by endocytosis are loose in the cytoplasmic environment. As vesicles are carried along fibres by motor proteins, their contents are brought to organelles, where they fuse with membranes. They release the chemicals they contain. Vesicle transport can be stimulated by an increase in Ca^{2+} ion concentration which leads to exocytosis. In this process, the vesicle membrane fuses with the cell membrane and vesicles can [illegible] whether proteins, neurotransmitters or other chemicals are released into the extracellular environment. (Petunia, In class)

When shown what she wrote, Petunia said: "Oh that one, I didn't know what I was talking about. [. . .] For this explanation, I kind of used things that I knew about other processes. Assumed things. Some of it even came from my basis in 8th grade biology." (Petunia 1: 513-526) Her explanation was a causal chain of different organelles, but lacked many of the details of a deeper mechanistic explanation. Petunia believed that she used the M, C, and H components naturally, and struggled with the A, but our analysis indicated that the M component was absent in both explanations. In other words, Petunia misjudged what her explanations contained and how she was communicating her understanding.

Growth

Petunia was able to use all MACH components after being taught about the model and throughout the remainder of the semester (Table 3.3). All of her explanations included each of the components with appropriate details after the intervention. Related to the struggles she perceived, she incorporated Analogies. For instance, when she read over her problem set explanation of vesicle trafficking, she explained, "Here is my analogy. Item ordered on the internet and shipped to the person desiring the item. Shipping proteins. So I would not have put that in there unless I was trying to MACH model it" (Petunia 1: 549-552). She intentionally addressed each component including and overcame the challenges that we identified (M) as initially missing and those that she perceived (A). Petunia did not have a gradual transition to using the MACH components. She immediately used the components each time she was asked, as reflected in the following conversation:

> Petunia: It isn't so much that I learned how to explaining things through it but I learned how to refine my explanations, or like are they thorough enough and complete.
> Interviewer: You felt like before you, you didn't have difficulty explaining?
> Petunia: No, not really, but now it is more structured and I have more

> direction, it was something that I didn't know I was missing direction in. I never thought about how to explain things. (Petunia 1: 285-291)

Petunia used the MACH to help her create concise, structured, and complete explanations. Her problem set, exam four and oral explanation were about a mechanism impacted by thalidomide, a drug that acts as a teratogen. By comparing these three explanations, one can see evidence of how her explanatory structure changed. In the problem set (Figure 3.4A), she explained:

> Thalidomide was discovered through a variety of experiments including one that involved the observation of rabbit eyes when exposed to thalidomide packets. [...] Thalidomide works like a faucet valve in early development. [...] Thalidomide is socially significant because it was originally used as a painkiller to ease symptoms of morning sickness in pregnant women, but it was found to be teratogenic [...] Thalidomide then intercalates into DNA, it is thought to do so at guanine residues. This intercalation leads to inhibition in the production of certain proteins. (Petunia, Problem set)

Her explanation contained all the components and ample detail, but treated the MACH model as an ordered process rather than as a component model. The explanation was a list of factual statements rather than a fully integrated explanation. In reflection, Petunia noted what was happening. "It kind of seems like I ordered in the MACH way and that is why it didn't line up" (Petunia 1: 575-576). Petunia was cognizant of a shift in how she was using and conceptualizing MACH. She reflected:

> So when we were first learning it was like - oh wait, so we have to go in that order so it has to be split up. [...] I feel like there is a jump from hey guys here is this tool to this is my personal use of it and you can incorporate it in various parts of an explanations, various forms within your explanations, so it is taking that to actually using it. (Petunia 1: 364-370)

For Petunia, it was not until she practiced using the model that she combined the information and "various parts" into a coherent explanation with a flexible flow. For example, her exam four explanation read (Figure 3.4B):

> [Thalidomide] has gone from being initially used to prevent nausea in pregnancy, to being the guilty cause of many babies' deformities, to being used today as a medicine for leprosy and multiple-myeloma. [...] Scientists used affinity purification beads to isolate thalidomide and its binding proteins. Scientist found that it binds with a strong specificity to cerebelon (CRBN) protein. (Petunia, Exam 4)

She improved her ability to communicate a large amount of information by mixing the components. She introduced her mechanism with the *Context*, continued with the *Methods* used, and then transitioned to the *How*. The remainder of the explanation was integrated and revisited each component. Overall, Petunia used all of the MACH components immediately after the intervention, but took time and practice to integrate the components into a coherent explanation.

Why Petunia found the MACH model useful

Petunia was a strong student who, like others, overcame her initial struggle with including the *Methods*. She also was able to write a fluid explanation. It is worth understanding the reasons why the MACH model affected her ability to explain. She summarized her views succinctly during the interview: "Efficiency is the one word I would use to describe this models impact on me. Efficiency of explanation, efficiency in analyzing that paper, and efficiency in learning without going through the stuff I know before I can find the stuff I don't." (Petunia 1: 641-663) Petunia included as outcomes of the MACH an efficient way to communicate concisely and completely, to analyze literature, and to monitor her understanding.

First, as a student she used the model to ensure that her explanations contained all the components. She states:

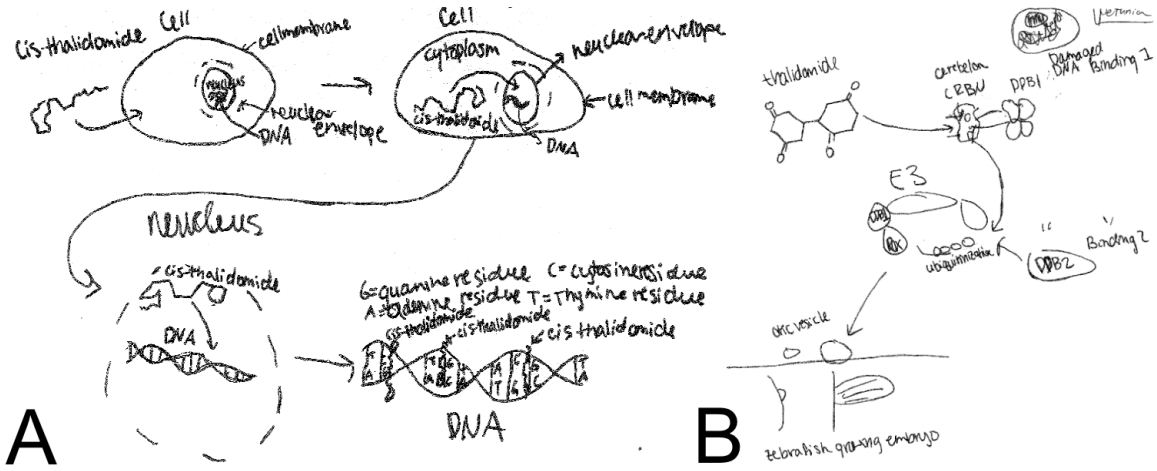

Fig. 3.4. Drawings by Petunia of the mechanism affected by thalidomide. Panel A contains a drawing from the problem set. Panel B contains a drawing from the interview. Both drawings by Petunia were retraced with black ink to improve image quality.

> The MACH model for me was just really interesting because it laid it all out. [. . .] I had those pieces but I never really thought about like why do I do this or what specifically do I say, like how does it work and why does it work, so the MACH model is just a cool way to check, check, check, check. Like that's cool. It works. It's formulaic, and I think it is a good tool for making sure that like I check myself on it when I explaining stuff now. So people are coming to me with questions for finals, and I am like okay wait, did I do this in my explanation, okay they should understand it. So, it is kind of cool like it is a checklist making sure that is thorough. (Petunia 1: 267-277)

By "laying out" all the components, Petunia knew what parts should be explicit in her explanation. She checked her explanations by using the MACH components as criteria to communicate completely and concisely. In addition to creating complete explanations, she used these criteria in other ways.

Second, she analyzed information from the literature by using the MACH model. For example, in regards to the independent research project, she declared:

> It was just an interesting experience because personally it was just like my learning structure is like functional. I can read information and retain it, and give it back to you, but I never tried to like learn a certain [way]. [. . .] It was a complicated paper and it took me a long time to piece apart and figure it out. I figured out what every diagram meant. That wasn't part of my presentation, but I figured out every single one. Like what was the significance, and what did they do, and what does this black dot mean, and using the model for that really helped because I could piece out for each method, for each part, for each how, for each diagram. Like how did that go together, which on my own I was just like this is too complicated and it would have probably taken longer. I am not going to lie to you because I would just scrounge up information instead of categorizing things. It was helpful. (Petunia 1: 641-655)

She found the MACH model to be helpful. This was because it provided a heuristic to analyze a research paper and to connect the *Methods*, *Analogies* (e.g. "diagrams"), *Context* (e.g. "the significance"), and *How* of the research. In this sense, the model guided her reading and comprehension of the science article since she was searching for the components of how experts explain. In addition to using the MACH model to analyze the scientific text, the model helped her monitor her understanding.

Similar to Felix, the MACH model helped Petunia monitor her knowledge and creation of explanations, as well as identify gaps in her understanding:

> Petunia: Again like the efficiency, and it does help me, [. . .] I use it as a check. So if I were to make an analogy, do I understand it well enough to do that, what else do I need to look into or research before I can do that. [. . .] Where are the holes? [. . .]
>
> Interviewer: What do you mean by the holes?
>
> Petunia: It is just like the holes in my knowledge of the topic or that understanding of what is happening because sometimes I can look at a page of notes and read and be like okay we are good, and then we'll ask a test question and it's like ohh that one specific things just wasn't there. [. . .] If I imagine giving an all inclusive explanation, I can find most parts that I am not sure on or that I am not as in-depth about. Again, using the model of, you know if I am going through the How and like and then, obviously I got to study that part. That is all.
>
> Interviewer: So it helps you fill in those gaps, the holes you are talking about it. Is it a way to monitor?
>
> Petunia: Almost like, you can read something and not know you are missing anything until you lay it all out and sometimes that is hard to do. And, a model like this you can see each part and break it down and this the part where I might be a little weaker or less in length. (Petunia 1: 328-354)

Petunia used the MACH model to identify the parts she knew and the parts she did not know. She was able to identify gaps in her explanations and to help her focus on her weaker components. Her account suggests that the model allowed her to make insightful judgments about her learning and to self-monitor her explanations.

Recommendations

Petunia felt that the presentation of the MACH model as distinct components encouraged students to place explanations in the MACH order – as in first, M, and then, A, C, and H. Petunia recommended that the use of the model could be improved by the instructors giving students clearance to use MACH in their own way. She felt that if students could incorporate the MACH components into their personal explanatory style, this would prevent students from using it in an ordered manner as Petunia initially did.

Summary of Petunia

Petunia's interview and analysis of her work provided insights into why a top student might benefit from using the MACH model. Similar to most other students, her explanations lacked components before the intervention, but she used all the components immediately after the intervention. The structure of her explanations changed across the semester – becoming less ordered and more integrated. Finally, our analysis of Petunia suggest that these changes occurred because the MACH model enabled her to explain completely and concisely, to analyze text, to monitor her understanding, and to identify gaps in her understanding.

3.4 Discussion

3.4.1 Summary of results

From our mixed methods study, we were able to draw a few conclusions about how students use the MACH components and the effectiveness of the MACH model as a teaching intervention for our sample population. Additionally, we were also able to make some claims about why the intervention with MACH affected the students we interviewed.

How the MACH model affects explanations

Most students used three of the four MACH components when explaining before the intervention (A, C, and H). This finding implies that students have an intuitive sense of causal explanation about biological entities. Student explanations fit a mechanistic view, and students place these into a context and add analogies with little difficulty. However, students rarely incorporate the research *Methods* into their explanations. Despite the fundamental role of data, tools, and procedures related to explaining mechanism, students tend to overlook *Methods*. Students are able to use all the MACH components with practice after the intervention. Thus to answer Research Question 1 -how does using the MACH model change the explanations written by life science students -one can conclude that the MACH model permits students' to maintain use of the *Analogies*, *Context*, *How* components, and to increase use of the *Methods* component when explaining.

The intervention results indicate that a targeted intervention can help students develop domain-specific knowledge – in this case, how to create explanations in biology. Given that the MACH components represent how experts explain biological mechanisms, students increased use of the components indicates improved domain-specific knowledge. Consistent with other research on expertise, this ability was developed through deliberate practice (Ericsson & Charness, 1994). Altogether,

when a model of the explicit components of a biologist's explanation is provided and opportunities to practice are given, students produce explanations that contain the same components.

Why students find the MACH model useful

Students who had varied success using the MACH model illustrate why they find MACH to be useful. For instance, both Petunia and Felix faced difficulties, and overcame those difficulties with deliberate practice. Felix had difficulty recognizing and relating the *Methods* that were presented in lecture to his explanations. For an instructor, it is informative to recognize that Felix thought that the *Methods* were not presented in class. In this sense, he needed practice both identifying and using the M component, but eventually he explains with the M component and even uses the model to explain the stomata guard cells he researched. Similarly, Petunia, a top student, believed she was using the M component before learning about the MACH model, but she had overestimated her abilities since her early explanations did not contain *Methods*. Later, Petunia included all the MACH components but found interweaving the components to be a challenge. With practice, she created explanations about mechanisms that integrated the MACH components and used the model to categorize the information she read. Future instructors could assist students to transition from thinking about MACH as a stepwise procedure towards seeing it as a holistic description. Additionally, instructors should be aware of that students have trouble identifying the *Methods* in the lecture and in their own writing. Both students overcame challenges related to misjudging the presence of the *Methods* component after using the MACH model.

To answer Research Question 2 - why do students think learning about the MACH model is useful, if at all - we found that the MACH model impacts the students' explanations by aiding them to self-monitor, to communicate complete and concise explanations, and to recognize gaps in their understanding. These findings

are consistent with what is known about expertise (Chi, 2006) and they connect to other findings related to explanations.

Two of the skills reported by students when using the MACH model relate to the practices of experts. Students begin to self-monitor their performance on tasks and seek new information to fill in their gaps as experts do (Chi, 2006). By using the model, which explicates how biologists explain, students are beginning to behave like experts. On the other hand, improved monitoring may be related to the findings that explanations about procedures are less susceptible to illusions of explanatory depth compared to explanations about natural phenomena (Rozenblit & Keil, 2002). Students who use the *Methods* component may better assess their knowledge. Rather than basing their assessment of knowledge on their knowledge of the phenomenon, students are assessing in combination with their knowledge of procedures. A memory illusion occurs anytime there is a misjudgment about memory (Roediger III, 1996); thus, a tool, such as the MACH model, that helps learners to monitor their understanding may have implications for meta-cognition research. Altogether, teaching students to use the MACH model may resolve many difficulties faced when learning biology.

3.4.2 Relation to other research

In light of the research presented here, some previously studied student difficulties related to mechanistic explanations are worth revisiting. First, Abrams and Southerland (2001) reported that primary and secondary students inappropriately address 'how' explanations. Conversely, our research indicates that students used the H component before and after the intervention. Second, our results show that students use H and explain entities, activities and organization in a way that transcended levels of organization. These results go against findings from a number of reports that secondary students have difficulty transcending levels of organization (Bahar et al.,

1999; Duncan & Reiser, 2007; Marbach-Ad & Stavy, 2000).These discrepancies may be due to the different education levels of students.

Furthermore, our students, like biologists, use *How* in conjunction to *Analogies*, which often contains language about purpose, needs, and stories. These analogies have traditionally been viewed as indicative of misconceptions or alternative conceptions. However, biologists are known to use these analogies as well (Trujillo et al., in press; Zohar & Ginossar, 1998). When using the MACH model, students have the creative clearance to use less formal ways of explaining in addition to the mechanistic way of explaining. Thus researchers may benefit from the MACH model since it portrays the plurality of components used by practicing biologists to explain.

3.4.3 Implications of this study

Given the promising results of this intervention, the MACH model can be applied to education research, science research, and education in other ways. First for education researchers, this study should be replicated to understand the effects of the intervention in other populations and institutional settings. Second, education researchers may be interested in using the MACH components as indicators of expert-like explanations in content such as textbooks, lectures, grant proposals, and online media. The MACH model may guide future research questions or be used to analyze data. Of relevance to the interview with Petunia, researchers may start measuring the blend of components and language usage within an explanation in addition to the presence of components, and more deeply investigate the nature and quality of the explanations pertaining to each component. Third, researchers may investigate how MACH applies beyond biology. For example, the MACH model can be combined with other prominent models, such as in chemistry education, the Concept-Reasoning-Mode (CRM) model (Schönborn & Anderson, 2009) or Johnstone's triangle (Johnstone, 1991). For instance, the CRM model represents the components of conceptual understanding, reasoning abilities, and visual abilities used by students to

understand, interpret, and generate external representations such as explanations or visuals. If combined for a new purpose, the CRM model may extend MACH beyond its current focus to include these aspects. The MACH model holds potential for researchers to better understand the teaching and learning of explanations both within and beyond biology.

Practicing scientists, both biologists and non-biologists, would benefit from using the model as well. MACH can make explicit what writing should contain within press releases, grant proposals, and explanations to the public in order to communicate effectively. The model may assist with both dissemination of research findings and improving scientific literacy of non-scientists.

For biology educators, the MACH model is an evidence-based teaching tool that produced favorable results by helping our students create and evaluate explanations. These results meet a recommendation from *Vision and Change* (Brewer & Smith, 2011). To extend the MACH model's use, educators may wish to create learning objectives, structure lectures and learning activities, and assess students around particular components. For instance, initially students did not incorporate *Methods* into their explanations, and knowing this, a biology teacher may wish to assess and teach *Methods* explicitly with the MACH model. Alternatively, an instructor may structure a curriculum with other approaches to encourage students to consider data and experiments, such as with the CREATE structure of Gottesman and Hoskins (2013). Both the MACH model and the results of the intervention are useful for biology educators who wish to teach students to explain and develop domain-specific knowledge. Overall, the MACH model and its components hold great promise for additional research inquiries and applications for teaching and learning.

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3.7 Supplement

Formula 1: McNemar's Exact Test

$\phi = \frac{\theta}{1-\theta}$

$H_0 : \theta = 0.5$

$H_1 : \theta > 0.5$

McNemar's exact test is an odds ratio test where θ is the parameter for a binomial distribution, $B \sim$ Binomial (b + c, θ) such that B is a random variable associated with b, where $B \in \{0, 1, \ldots, b + c\}$, b is the number of students who went from present to absent for a given component between exam two and exam four, and c is the number of students who went from absent to present. The null hypothesis is that θ is equal to 0.5, and the alternative hypothesis is that θ is greater than 0.5 (Fay, 2010).

Formula 2: Cohen's Kappa

$\kappa = \frac{P_a - P_e}{1 - P_e}$

Where κ is Kappa, P_a is the percent in agreement between raters, and P_e is the percent in agreement expected by chance. Cohen's Kappa is the degree of agreement by the raters relative to what would be expected by chance, where κ of 1 is perfect agreement and κ of 0 is agreement by chance alone (Stemler, 2001).

Table 3.5.
Relevant prompts used throughout intervention and data collection.

Source	**Prompt**
Exam two	Choose any ONE specific example of a protein conformational change that plays an important role in the regulation (control) of a response to light by a plant cell. Write a maximum 1-page essay to explain the mechanism of your selected process. Draw and label a diagram as part of your explanation. Describe all the details you know about the phenomenon.
In-class worksheet	Hand-write a paragraph to explain how vesicle trafficking occurs within the cell. Draw and label a diagram as part of your explanation. Describe all the details you know about the phenomenon.
Problem set A	Write a maximum 1-page essay to explain the mechanism of how vesicles traffic within a cell. Draw and label a diagram as part of your explanation. Describe all the details you know about the phenomenon. Use the MACH Model, presented by Caleb Trujillo, to guide and structure the content of your explanation. Make it clear which parts of your explanation correspond to each component of the model.
Problem set B	Generate an original explanation about a biological mechanism of your choice using the MACH model mechanism components handouts as guidelines.
Exam three	Choose any ONE specific example of a mechanism that plays an important role in the response of a photoreceptor in the retina to light. Write a maximum 1-page essay to explain the mechanism of your selected process. Draw and label a diagram as part of your explanation. Describe all the details you know about the phenomenon. Use the MACH Model, presented in class by Caleb Trujillo, to guide and structure the content of your explanation. Make it clear which parts of your explanation correspond to each component of the model.
Oral explanation	Today I would like you to talk about cellular mechanisms. Lets take a moment to think. Take your time and start thinking about these types of processes. Take as much time as you want, don't rush, just relax and think about them for a while. Try to imagine it; mechanisms inside the cell, think about everything you know about what these are and how do they work. Ok, what are you thinking about now? Tell me slowly and clearly, take your time (modified from Schnborn & Anderson, 2009, Trujillo et al. In Review).
Exam four	Choose any ONE specific example of a mechanism that you learned about this semester. Write a maximum 1-page essay to explain the mechanism of your selected process. Draw and label a diagram as part of your explanation. Describe all the details you know about the phenomenon. Use the MACH Model, presented in class by Caleb Trujillo, to guide and structure the content of your explanation. Make it clear which parts of your explanation correspond to each component of the model.

Table 3.6.
Data of students use of MACH components for explanations from exam two and exam four. 1 indicates presence of component; 0, absence.

	Exam 2				**Exam 4**			
Student	M	A	C	H	M	A	C	H
1	0	1	1	1	1	1	1	1
2	0	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1	1
4	0	1	1	1	1	1	1	1
5	0	1	1	1	1	1	1	1
6	1	1	1	1	1	1	1	1
7	0	1	1	1	1	1	1	1
8	0	1	1	1	1	1	1	1
9	0	1	1	1	1	1	1	1
10	0	1	1	1	1	1	1	1
11	0	1	1	1	1	1	1	1
12	0	1	1	1	1	1	1	1
13	0	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1
15	0	1	0	1	0	1	1	1
16	0	1	1	1	0	1	1	1
17	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1
21	0	1	1	1	1	1	1	1
22	0	1	1	1	1	1	1	1
23	0	1	1	1	1	1	1	1
24	0	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1
Relative percent of students with presence								
	32%	100%	96%	100%	92%	100%	100%	100%

CHAPTER 4. DISCOVERING PEDAGOGICAL CONTENT KNOWLEDGE (PCK) TO HELP STUDENTS UNDERSTAND HOW MOLECULAR AND CELLULAR MECHANISMS ARE EXPLAINED

Authors: Caleb M. Trujillo, Trevor R. Anderson, and Nancy J. Pelaez[1]

> When one examines the other protein assemblies known to operate in cells [. . .] one is sometimes reminded of the many irrational complexities of a Rube Goldberg cartoon.
>
> *Bruce Alberts*

To illustrate a general strategy for developing pedagogical content knowledge (PCK), or subject matter knowledge for teaching, we examine how to teach undergraduate students to explain molecular and cellular mechanisms. Explaining such systems in the classroom presents challenges due to the immense complexity and abstract nature of the content. When any new instructor is faced with the need to address these and other challenges, they need PCK, which encompasses domain knowledge plus knowledge for representing the subject to others. Here we propose a general approach for developing PCK by asking: how does one help instructors and students understand and include the components biologists use when explaining molecular and cellular mechanisms? To address this question, a first study was conducted to model the components used by biologists to explain molecular and cellular mechanisms, then during a second study, the produced model was presented to students as part of a teaching intervention, but presented here, students exhibited difficulties when integrating the

[1]All studies were performed under the approval of the Institutional Review Board (protocol number 120301239 and 1306013717).

components of explanations during the teaching intervention, so knowledge of these difficulties was used to further develop useful instructional materials including a physical model, teaching activities, and a rubric to make the components comprehensible to students. This report, written for physiology and biology instructors, presents both knowledge and resources for explaining molecular and cellular mechanisms in undergraduate biology courses, and a logical design process to improve instruction in general.

4.1 Introduction

Molecular and cellular mechanisms are notoriously difficult to explain in the classroom. These mechanisms are characterized by a complexity of interactions between intangible molecular components, which are often represented with scientific models of abstract systems (Tibell & Rundgren, 2010). Alberts (1998) has gone so far as to compare protein machines to the cartoons of Rube Goldberg, due to their irrational complexity. The problem, then, is first to understand how practicing scientists explain such immeasurably complex systems, and then to help instructors and students develop the same expertise for explaining molecular and cellular biology.

One useful way to conceptualize the nature of teaching and learning is to equate learning to developing expertise. An effective teacher helps novices (students) become more expert-like and this is done by conveying knowledge of a particular discipline. Experts and novices tend to differ in how they perform skills within a specific field. For instance, experts are known to excel at finding best solutions, chunking large amounts of information to memory, recognizing underlying concepts, constraining and analyzing problems, self-monitoring progress, thinking strategically, seeking useful information when opportunities exist, and using minimal cognitive effort and little conscious thought (Chi, Feltovich, & Glaser, 1981; Chi, 2006; Egan & Schwartz, 1979). On the other hand, novices tend to produce less accurate solutions,

chunk smaller amounts of information, face difficulty when representing problems, focus on superficial features of given scenarios, fail to identify underlying principles, and make inappropriate inferences from cues (Chi, Feltovich, & Glaser, 1981; Chi, Glaser, & Rees, 1981). These differences can be attributed to the domain-specific knowledge being well-developed by experts and lacked by novices.

Domain-specific knowledge is deep, content-rich, and principled knowledge. Domain-specific expertise is not an innate trait of individuals; rather it develops over many years of deliberate practice (Donovan, Bransford, & Pellegrino, 2000; Ericsson & Charness, 1994). For novices to gain expertise in a given discipline, they must develop the domain-specific knowledge, and one way to do this involves deliberate practice. The role of an educator is to guide students towards practicing relevant disciplinary skills. Therefore, a challenge for an expert who teaches is to make this deep knowledge comprehensible to students so that they may develop expertise. Our goal for this paper is to illustrate using molecular and cellular mechanisms as our context a method for creating instructional resources to guide students towards practicing relevant disciplinary skills.

In the classroom, the problem of explaining molecular and cellular mechanisms presents many obstacles for the teacher who provides explanations and for students who interpret and generate their own explanations. For instance, explanations about molecular systems are often entangled with everyday language (Tibell & Rundgren, 2010) and the way a scientist explains to a student is different than the way he or she explains to a scientist (Treagust & Harrison, 1999). Therefore a teacher may deliver an explanation about molecular and cellular mechanisms with elements that differ from those a biologist would use to explain such systems. Additionally, students tend to overestimate their knowledge of explanations about hidden and hierarchical processes (Rozenblit & Keil, 2002), so many students may have an illusion of understanding molecular and cellular mechanisms. Furthermore, many education reports have found that students, across many age groups, often create explanations of molecular and cellular processes that differ from the explanations accepted by scientists (Abrams &

Southerland, 2001; Duncan & Reiser, 2007; Lewis, Leach, & Wood-Robinson, 2000; Marbach-Ad, 2001; Marbach-Ad & Stavy, 2000; Treagust & Harrison, 1999). Therefore, a life science educator must not only make their domain-expertise understandable when teaching, but they must instruct in a way that is sensitive to the documented difficulties faced by student learning the specific subject matter. Simply put, there is a need to address explaining of molecular and cellular mechanisms in the context of instruction so that students develop an understanding of such systems and are able to interpret, evaluate, and generate explanations with the elements that biologists include when they explain.

The task of improving undergraduate biology courses to address explanations of molecular and cellular mechanism poses additional challenges. For instance, according to *Vision and Change* (*VC*) (Brewer & Smith, 2011), a document which provides recommendations to improve undergraduate biology courses,

> Many faculty still express uncertainty over how to better connect teaching with learning, how to make approaches to teaching biology align better with the practice of science, and how to fine-tune undergraduate biology courses to better meet the needs of the diverse student bodies we all serve. (Brewer & Smith, 2011, pg.21)

As such, there is a need to provide guidance to both instructors and students so that they may overcome the problem of explaining, and in so doing, understand and include the components used by biologists when explaining molecular and cellular explanation.

The challenge of linking subject matter knowledge and effective teaching is not new. Three decades ago, Shulman identified a lack of scholarship about how knowledge of a subject (e.g. biology) translates to how one teaches, which he termed the "missing paradigm" (Shulman, 1986). According to Shulman, effective teachers have subject matter knowledge, curricular knowledge, knowledge of teaching methods, and a less studied form of knowledge specific for teaching a given subject (Shulman,

1986). To address the gap in scholarship, Shulman forwarded the idea that teachers possess pedagogical content knowledge (PCK). He states:

> [PCK] goes beyond knowledge of subject matter per se to the dimension of subject matter knowledge *for teaching* [*sic*]. [...PCK includes] the most useful forms of representing those ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations – in a word, the ways of representing and formulating the subject that make it comprehensible to others. (Shulman, 1986, pg. 9)

A teacher with PCK understands both the representations of subject matter knowledge that are effective for teaching and what aspects are difficult for learning a given subject (Shulman, 1986; Van Driel, Verloop, & de Vos, 1998). As such, knowledge of the subject matter to be taught is a prerequisite for developing PCK, which is gained through teaching experience (Van Driel et al., 1998). To compare a discipline expert and an excellent educator of that discipline, both have knowledge of the subject domain, but the individual with PCK has an additional understanding which allows them to convey and represent the subject knowledge so that is easy to understand for novices. As with most skills, PCK develops through practice, and in the educator's case, practice accumulates by testing representations for teaching, by examining evidence of its impact on student learning and by deliberately refining and redesigning the representations. In the context of physiology and the other life sciences, PCK encompasses the ways of representing biology to make biological processes comprehensible to students, as well as an understanding of student learning so to help them to develop life science expertise.

In order for life science teachers to develop effective PCK, they must have the necessary subject matter knowledge and knowledge of their students' performance when learning a given skill. Therefore, to address how one develops PCK in the context of explanations about molecular and cellular mechanism, this report asks: How does one help instructors and students understand and include the components biologists use to explain molecular and cellular mechanisms? To address this question,

we proceed through four stages. First, we model the components that scientists include to explain molecular and cellular mechanisms. Second, we modify the resulting model to communicate the components clearly to students in the classroom. Third, we teach students to use the model to explain and analyze explanations. Fourth to address challenges that emerge, we modify the teaching materials in light of the performance of students and develop a rubric. In this report, we review two previous studies, which address the first three stages, and present teaching resources designed to address an emergent challenge of teaching the components used by biologists to explain molecular and cellular mechanisms. As such, this report has been written for life science educators so that they may adopt a general process for instructional design to discover and apply PCK for teaching undergraduate biology students.

4.2 Develop a model for explaining

The components present in biologists? explanations of molecular and cellular mechanisms were identified in a previous study. These components define four areas of subject matter knowledge for PCK that were identified starting with a literature review. First, according to the literature (van Mil, Boerwinkel, & Waarlo, 2013; Machamer, Darden, & Craver, 2000), we defined molecular and cellular mechanisms as explanations which address "*how the component entities of a biological phenomenon interact at the molecular, microscopic, and macroscopic levels to produce detectable changes in state, activities, and spatial and temporal organization.*" (Trujillo, Anderson, & Pelaez, in press) Next, in a study informed by a modeling framework (Justi & Gilbert, 2002), we tested an initial model from the literature review by analyzing interviews of seven biologists who conduct research on molecular and cellular mechanisms in different biology sub-disciplines. Their explanations of the mechanisms they investigate in their laboratory research were analyzed for themes (Trujillo et al., in press). The results informed the creation of a new model which represents four components that biologists include when explaining molecular and cellular mechanisms.

The four components are represented by M, A, C and H as outlined in the next paragraphs.

The excerpt in Figure 4.1 is an example from an interview with Buck, a participant scientist, who explained how hormones from fat tissue promote or repress cancer growth. The analysis of transcripts like this one indicated that a sample of scientists from a Midwestern research university in the U.S. include four components when explaining molecular and cellular mechanisms, which are indicated by the letters and colors. For instance, Buck's explanation included research *Methods* (M, red) in his explanation when he said:

> One of the things that we did to get into this area was to look at and try to identify other genes that leptin could regulate in cancer cells to promote their growth. So, we did some microarray studies. We took leptin and treated human breast cancer cells with leptin, and then we isolated the cells, harvested the RNA fraction of it, converted the RNA to DNA, and ran some microarrays on it. (Buck, physiologist and cancer biologist)

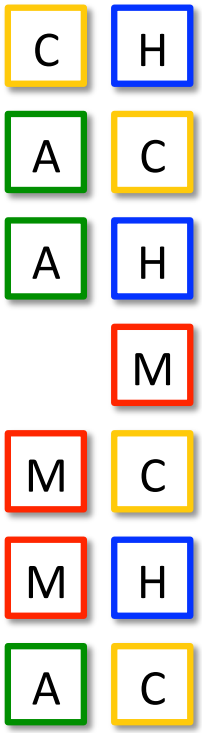
Methods are present due to the references to data, procedures, and tools such as microarray data. Buck used *Analogies* (A, green) such as referring to analogous signaling pathways and he drew scientific models, such as Figure 4.2 to explain the pathways affected by adiponectin. Additionally, Buck used less precise language when he states "how these cells induce their function," and "[leptin] basically causes the cell to secrete things [. . .] to modulate the extracellular environment to promote tumor growth and aggressiveness" and these parts of his explanation behaved as *Analogies*. This is because the terms attribute entities with having human-like features such as "aggressiveness" or the ability to "promote." When Buck said, "obese people have higher levels of this one hormone leptin, and decreased levels of this other hormone adiponectin. And when those ratios are out of sync that way during obesity, they promote cancer," he included *Contexts* (C, yellow) by addressing the social aspects of cancer and obesity to show the importance of the explanation. He also places his explanation in a biological context by focusing on human breast cancer cells. Finally,

Buck explains *How* (H, blue) leptin works by identifying leptin's interaction with a receptor at the cell membrane to produce signaling activity and gene expression changes. He states, "there has been pretty extensive work done on what the signaling pathways leptin induces once it interacts with a receptor. And that is the JAK/STAT pathway and the MAP Kinase." Later he details the mechanisms activated by adiponectin:

> This adiponectin, which actually is a complex of three monomers of adiponectin, binds to this receptor, which is like a G-Protein Coupled Receptor. But it is interesting because of the way that it sits in the membrane. It has a carboxy-terminus on the outside of the cell so it is inverted from what normally happens, the way the receptor sits. But when you have binding to the receptor you have an association and activation of APPL, which is a kinase that then leads to the AMP Kinase. And that is a central regulator of a lot of different processes, including fatty acid oxidation. (Buck, physiologist and cancer biologist)

When Buck explains he refers to specific entities and changes in states, activities and organization in time and space to address How the mechanisms works. Like Buck, all of the other participating biologists included four components to explain the mechanisms they investigate. These four components, which are carefully defined in Table 4.1 (page 113), include: references to research *Methods* (M) that inform the mechanisms; *Analogies* (A) such as models and actors, to illustrate and tell a story; a social or biological *Context* (C) to show the explanation's importance; and *How* (H) the mechanism works (Trujillo et al., in press). The four components informed the MACH model, a representation of components included by biologists when they explain molecular and cellular mechanisms (Trujillo et al., in press). As shown by the codes represented by the symbols and colors in Figure 4.1, Buck's excerpt naturally integrates each of the MACH components. Buck's excerpt naturally integrates each of the MACH components. For the purposes of this report, we define integration as the act of combining the essential MACH components to make a coherent, whole explanation with systematic or logical connections among the components in-

cluded when explaining the mechanism. By coherent, we mean the explanation of the mechanism is written or spoken with logical integration of diverse elements, with relationships expressed in a clear way such that the components work closely and well together. In other words, the components are connected in a manner that is easy to understand. An explanation lacking the essential parts or produced so that it lacks systematic or logical connections makes it unintelligible to the audience, so that would be considered non-integrated. Buck has produced an integrated explanation since it combines all of the components as a whole to make the explanation understandable because it is logically ordered and the components are integrated. Thus, the MACH model provided a useful starting point to help students understand the components for explaining molecular and cellular mechanisms in the classroom.



We know that obese people have higher levels of this one hormone leptin, and decreased levels of this other hormone adiponectin. And when those ratios are out of sync that way during obesity, they promote cancer. [...] Regarding the signaling, how these cells induce their function, they are both protein hormones, so they bind to receptors on the cell surface. And for leptin, there has been pretty extensive work done on what the signaling pathways leptin induces once it interacts with a receptor. And that is the JAK/STAT pathway and the MAP Kinase that promote proliferation and there are so many different players, but the interesting thing is that people have defined it as a similar pathway used by other hormones in regulating proliferation. [...] One of the things that we did to get into this area was to look at and try to identify other genes that leptin could regulate in cancer cells to promote their growth. So, we did some microarray studies. We took leptin and treated human breast cancer cells with leptin, and then we isolated the cells, harvested the RNA fraction of it, converted the RNA to DNA, and ran some microarrays on it. [...] There were a couple [of genes] that we were really interested in that came up. And one of them was a collagen. [...] With our subsequent *in vitro* studies that showed that leptin increased different collagens, it seems that leptin not only promotes proliferative pathways but it basically causes the cell to secrete things, growth factors and collagens, to modulate the extracellular environment to promote tumor growth and aggressiveness.

Fig. 4.1. The transcript of an explanation made by Buck, a physiologist and cancer biologist, as he explains the mechanism of action for leptin. Letters and colors represent coding of the text for the corresponding MACH components.

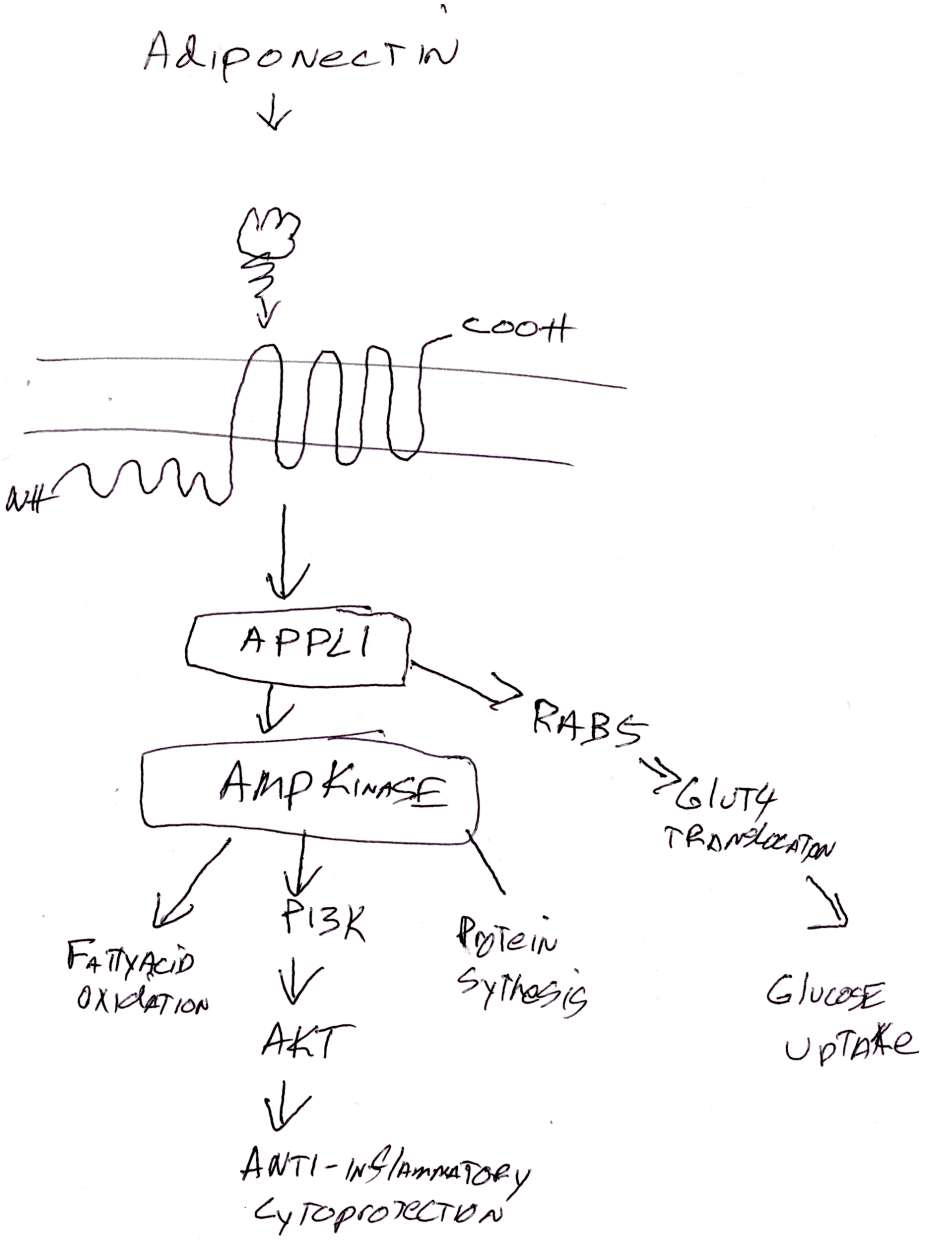


Fig. 4.2. A diagram made by Buck, a scientist, who used this diagram as a scientific model to explain the mechanism of action for adiponectin.

Table 4.1.
Operational definitions of the MACH components (Trujillo et al., In press).

Component	**When explaining molecular and cellular mechanisms, biologists...**
Methods	Include the research methods, such as, informative data, procedures, or instruments that inform how the mechanism works.
Analogies	Use a wide variety of analogies including models, visual representations, metaphors, and stories that treat molecules as if they have an intention or purpose.
Context	Contextualize around an important biological or social setting, such as, a type of organism or how the mechanism relates to a disease.
How	Include the How of the mechanism by addressing the spatial and temporal organization of entities and their respective activities.

4.3 Representing the MACH model for the classroom

Once the research with scientists was complete, the MACH model was ready to be modified for the purpose of helping instructors communicate the practices of scientists for teaching. The model, which was originally in the form of a Venn diagram (Trujillo et al., in press), was converted to a physical model. This was because the Venn diagram was not a suitable representation to make the components comprehensible to students, rather it was meant to visualize the overlapping use of the components by experts. To make a representation for students, a physical model was designed so that each component would be visible and distinct. The resulting tetrahedral MACH model makes information accessible with each vertex of the tetrahedron representing a component. Key terms for each component are printed on the model. For instance, the M (*Methods*) vertex includes "Tools, data, and procedures"; A (*Analogies*) has "Analogies, models, & narrative forms"; C (*Context*) has "Biological and social"; H (*How*) "variable states of entities, activities, & organization." By displaying the components as vertices, the distinct MACH components appear to be more comprehensible to students. Later, this tetrahedral was modified to include the

colors and symbols (squares, triangles, stars and circles), and this tetrahedral MACH model is available for instructors (Trujillo, Anderson, & Pelaez, 2014b).

4.4 Teaching students with the MACH model

Once we had a physical MACH model suitable for the classroom, we attempted to address the challenges of explanation by implementing teaching interventions using the tetrahedral MACH model in three courses with a wide range of students (Table 4.2). While learning objectives remained the same across the courses (Table 4.3), the lessons and their presentations were adapted to accommodate the biological context relevant for each course and the preferences of the instructors. In this way, content factors, teaching factors, educational context factors, and student factors that influence the successful transition of an explanation into the classroom were accounted for and revisited as each setting changed and new insights were gained (Treagust & Harrison, 1999)

Table 4.2.
The MACH model's use in three courses from two science departments.

Course	**Instructor**	**Semester**	**Lesson time**	**How many students**	**Context used as an example**
1. Biochemistry for life science majors	Anderson	Fall 2013	2 x 50 min.	53	Vesicle trafficking
2. Intro biology II	Pelaez	Spring 2014	1 x 50 min.	56	Vesicle trafficking
3. Biochemistry for health science majors	Anderson	Fall 2014	1 x 50 min.	75	Membrane transport

Table 4.3.
Learning objectives used to guide the development of lessons.

Learning objectives: Students will be able to . . .
Identify the MACH components when learning about a molecular or cellular mechanism.
Apply the MACH components to explain a molecular or cellular mechanism.
Create an explanation of a mechanism of the students choice using MACH.
Explain how a molecular or cellular mechanisms relates to their own daily life.

4.4.1 Teaching upper-division life science majors

In the first intervention, life science students in an upper-division biochemistry course (Course I in Table 4.2) viewed molecular animation of vesicle trafficking (Liebler, 2007), they created an explanation of vesicle trafficking, read a written explanation about the mechanism (Zierath & Lendahl, 2013) and rated their understanding of the mechanism. Then they received a lecture on the MACH model and how to use the tetrahedral model to explain, they analyzed a written explanation about vesicle trafficking to identify the MACH components included by the author, and finally they generated their own explanation of vesicle trafficking with the MACH model. The rationale for these activities was to expose students to a clear example of a mechanism, help them to understand the components they include and the components authors include in an explanation, and to teach students about MACH so that they may uses this as a lens to interpret and generate explanations. The first intervention occurred over two 50-minute course lessons, was intended as a pilot, and was videotaped. The pilot provided motivation to extend the MACH model into a more rigorous study.

4.4.2 Teaching introductory majors and non-majors

In a second course (Course II in Table 4.2), a similar intervention was successfully implemented and results from the study were compiled and reported (Trujillo,

Anderson, & Pelaez, In preparation). This intervention took place during one 50-minute lesson. As with the first intervention, the students performed the same tasks, viewing an animation, writing an explanation, reading, and rating their understanding. Then they learned about the MACH components and the tetrahedral model and applied these to analyze an explanation and generate their own. Similar to the first intervention, the lesson was videotaped. However, unlike the first, a mixed-methods study was performed to understand the impact of the intervention on student explanations (Trujillo et al., In preparation). Student explanations were collected from exams before and after the second intervention, paired for comparison, and subjected to analysis by coding for MACH model components. This analysis revealed that before the intervention most student explanations included *Analogies*, *Context*, and *How*, but unlike the scientists, less than 32 percent, included *Methods* (Trujillo et al., In preparation). The following excerpt exemplifies a response made by a student before the intervention.

> When blue light strikes a photoreceptor (i.e. Phot1) in the guard cells, high phosphorylation of the H^+-ATPase occurs as H^+ is pumped out of the cell. This results in the inside of the cell becoming more negative. Then, K^+ ions then begin entering via passive transport. Through secondary active transport, Cl^- ions enter as do some H^+ ions and some KCl is formed. As a result of the increased solute concentration inside the cell/negative membrane potential, water enters the cell. Overall, this process is responsible for the opening of the stomata in response to blue light. An influx of water is necessary for the essential increase in turgid pressure. (Course II, exam 2)

The explanation addresses how the Phot 1 receptor changes the states of the H^+-ATPase to change the solute concentration inside the cell (H). The context of the mechanism is within a guard cell (C), and a visual representation (Figure 4.3) serves as an analogy (A), but the student did not refer to any research *Methods* (M) that inform how scientists know about Phot 1. *Methods* were typically absent in responses

before the intervention. Overall, the above pre-intervention student explanation integrates some of the essential components into a coherent explanation, since the three components are well connected and easily understood, but due to the lack of the M component it is not fully integrated as Buck's explanation. If this student had added *Methods* in a coherent and well-connected manner, it would be considered fully integrated.

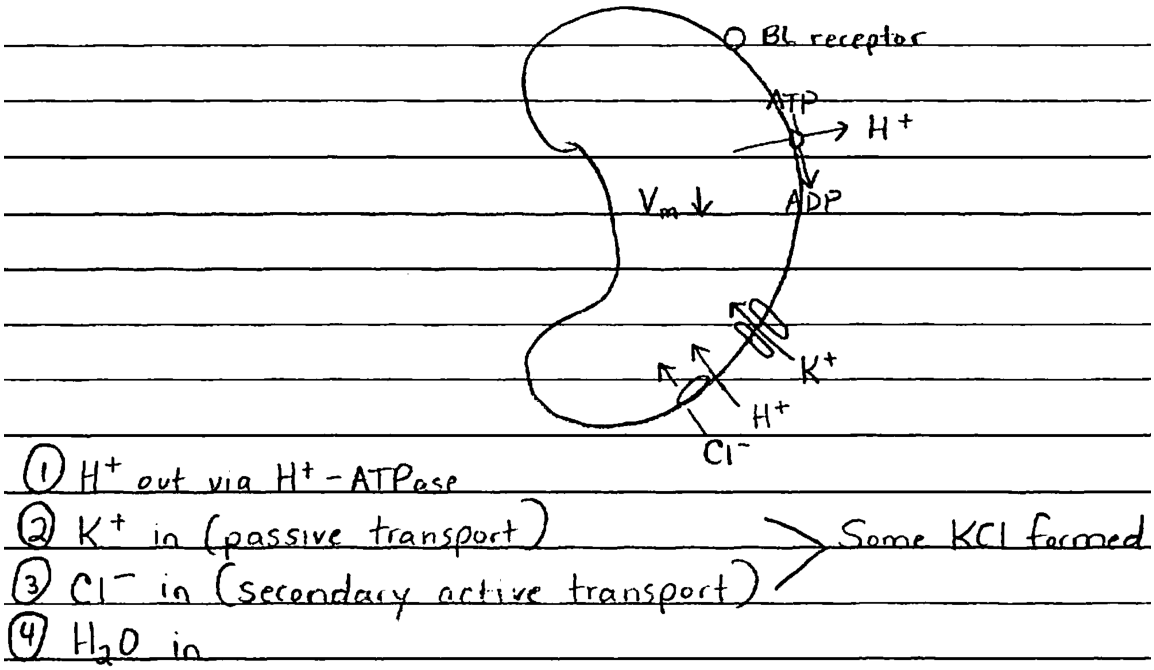


Fig. 4.3. A diagram made by a student to explain the Phot 1 mechanism (Course II, exam 2, before the intervention).

After the intervention, more than 90 percent of students incorporated all four components into their written explanations. The inference that the frequency of M component increased was supported by statistical analysis. Furthermore, inductive analysis of interviews revealed that students used the MACH model to self-monitor their understanding, to communicate completely and concisely, and to reveal gaps in their explanations (Trujillo et al., In preparation). However, a new difficulty was

revealed during this intervention when students struggled to integrate the components into a coherent explanation as biologists do (Trujillo et al., In preparation). For example, the following response made after the intervention failed to integrate the components, even though all four components were present.

> M - The photoreceptor in the retina was discovered by a German physiologist, Franz Christian Boll. The researchers found how the mechanisms that our eye receives the light signal [sic]. This mechanism is measured by voltage-sensing microelectrode and the intensity of the light. A - [Figure 4.4]. C - The importance of the experiment was to find the molecular mechanism of retina and find the treatment for a photoreceptor-mutated gene, such as retinitis pigmentia, color blindness. It was to understand how humans see things. H - When light, or photon, reaches it, rhodopsin sends signals to G-protein that activates the G-protein. The activation leads to activation of cGMP phosphodiesterase by GTP. The cGMP diesterase activation uses cGMP in the cell to produce 5'-GMP and closes Na^+ ion channels and hyperpolarizes the cell. (Course II, exam 4)

Figure 4.4 indicates the respective Analogy drawn by the student. Despite some grammatical errors, the student wrote appropriately for each of the components but did not integrate the components as an expert would. The post-intervention student explanation included all of the MACH components like an expert would but this explanation was dissimilar to the explanation made by Buck and the other participant biologists. The student did not explain as a coherent whole; the explanation is separated into distinct parts. This aspect makes the explanation less comprehensible for a reader than Buck's explanation. Such responses suggested a need to modify the intervention to emphasize integration of the MACH components.

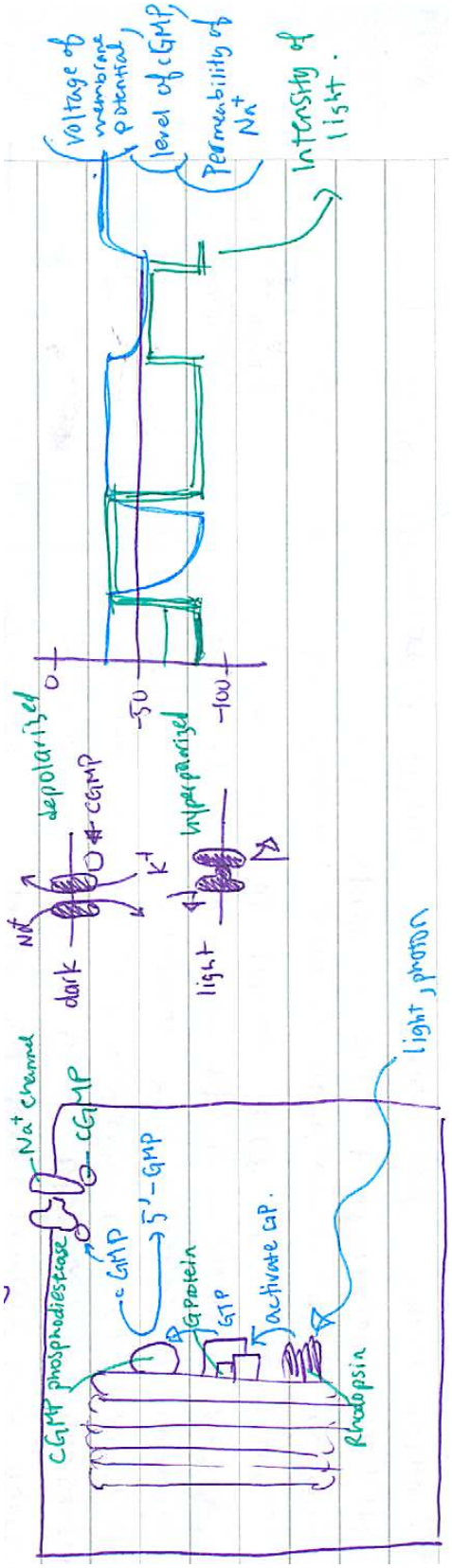


Fig. 4.4. Diagrams and a graph created by a student to explain phototransduction in the retina (Course II, exam 4, after the intervention).

4.4.3 Teaching upper-division health science majors

The third intervention (Course III in Table 4.2) provided an opportunity to apply the knowledge from the published intervention to help students integrate the components as a biologist would when explaining. Therefore, the intervention was modified and implemented in an upper-division biochemistry course for health science majors during a single 50-minute lecture. Unlike the preceding interventions, the third intervention focused on the topic of membrane transport in the context of cystic fibrosis, and the tasks and their order were changed compared to the previous implementations in order to give students more practice identifying how the components were integrated into a coherent explanation before they were asked to construct their own explanation (Table 4.4). Students in the third intervention read a one-page excerpt either from an article by Skwarecki (2014) or one by Trivedi (2013), they analyzed and they marked the excerpt as follows:

> Science research methods (Square); Models, figures, graphs, or analogies including anthropomorphic stories (Triangle); Biological and/or social contexts (Star); How the phenomenon works through physical causes (Circle); and Places where the above components blend and interweave (Checkmark). (Trujillo, Anderson, & Pelaez, 2014a)

Then they discussed their findings with a partner and shared their ideas with the class before they were given a presentation about the MACH components and the tetrahedral model, which helped to clarify ideas from the class discussion. The tetrahedral model had been modified to contain the matching symbols to facilitate matching the components they had identified in the written explanation with the model. Finally, the students were presented with another written explanation of the membrane transport mechanism of the cystic fibrosis transmembrane conductance regulator, which exemplified an explanation that included all of the MACH model components. No animation was presented, but the most notable change was unlike the two prior interventions. Students in the third intervention analyzed sample readings for the

components, written in student-friendly language, before a formal presentation of the MACH components. This was done so that students read and discussed the author's integration of the components before learning about the abstract aspects of the MACH model. In this way, integration was introduced to students before learning about each component in depth.

Table 4.4.
Tasks used in each course activity with order indicated.

Activity Task	**Course** (as per Table 4.2)		
	1	**2**	**3**
Watch an animation of a molecular mechanism.	1	1	-
Create an explanation about the animated mechanism.	2	2	-
Read a written explanation of a mechanism.	3	3	1
Rate an understanding of a mechanism.	4	4	-
Learn about the MACH components and the tetrahedral model.	5	5	4
Analyze reading for the MACH components.	6	6	2
Explain another mechanism using the MACH components.	7	7	6
Discuss with partner their partner the components in a written explanation.	-	-	3
Present the MACH components for a molecular mechanism.	-	-	5

The excerpt below contains an example of a student explanation after the third intervention. The student explains how electron transport is coupled to ATP synthesis using the MACH model in an integrated matter:

> [. . .] ATP is considered the "energy currency" because it converts readily to ADP, while releasing energy simultaneously to create muscular contractions within the body, as well as various intracellular interactions. The electron transport chain (see figure attached) [Figure 4.5] is a series of proteins within the mitochondria. The complex, comprised of 4 proteins, passes electrons through their interior, which powers a hydrogen ion pump. The pump creates a H^+ gradient across the inner membrane of the mitochondria. The gradient then powers the final protein, ATP Synthase, which as its name implies phosphorylates ADP to form ATP. The

> electron transport chain is the root cause of the hydrogen ion gradient; the chain uses reduction potential to drive the hydrogen pump and power ATP Synthase. A series of studies dealing with muscular contractions in the spine, inhibited the transport chain by forcing a powerful reductive agent to attach to the complex before one chain could pump hydrogen ions out of the matrix. By testing the number of contractions per minute, they could see a substantial decrease due to lack of 'available ATP'. (Course III, exam 3)

This response explains as an expert would by integrating the four components into a single coherent explanation. The student addressed how the research *Methods* would inform the mechanism by referring to an experiment that measured contractions in the presence of a reductive agent (Dinitrophenol was taught in class). The explanation included *Analogies* by naming ATP as an energy currency, by using everyday terms such as "power," and by drawing a scientific model (Figure 4.5). The response has a *Context* for the mechanism within the muscles of the spine. Finally, the *How* explains the creation of a potential to drive ATP Synthase to converting ADP to ATP by describing the electrons, hydrogen ions, and proteins (interacting entities) and changes in their states and organizations across time and space. This response exemplifies how well many of the students were able to address the components in an integrated manner. A quasi-experimental study with detailed pre-post measures of integration in student explanations are needed to make stronger claims about the impact of the third intervention on student explanations (See discussion).

4.5 Applying PCK to develop teaching resources

4.5.1 Sharing the materials for teaching with MACH

After the third intervention, we were encouraged by our colleagues to disseminate our resources so that other biology instructors may benefit from implementing the interventions or adapt the resources for explaining in their own classrooms. There-

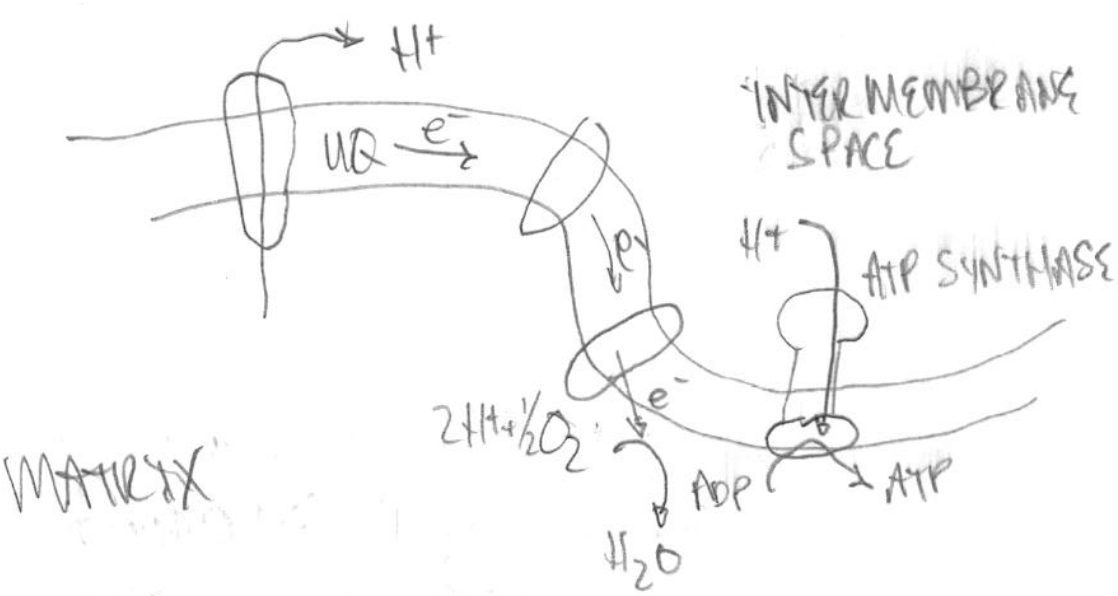


Fig. 4.5. A diagram of the electron transport chain and ATP Synthase to explain ATP synthesis produced by a student (Course III, exam 2, after the intervention).

fore, both the activity used during the third intervention, and the tetrahedral MACH model have been provided in pdf and doc or ppt formats so that any educator may modify these to suit their courses, students, teaching preferences and the content of their lessons (Trujillo et al., 2014a, 2014b).

4.5.2 Developing a rubric to evaluate student explanations

In addition to providing the teaching materials, we identified a need to evaluate the quality of students' explanations in a way that was practical for instructors and could provide feedback to students about their progress. To address this, a rubric was designed (Table 4.5, page 127) by looking carefully at student responses while focusing on three purposes (Table 4.6, page 128). These purposes were to be theoretically consistent with the explanations made by biologists when they explain molecular and cellular mechanisms, to be useful and practical for teaching instructors, and to be able to distinguish high-quality student explanations from low-quality explanations. With these purposes in mind, a performance-based rubric and the MACH model operational definitions were developed to assess the integration and quality of the MACH components in explanations of molecular and cellular mechanisms made by students (Table 4.5). As with the other produced materials, the rubric was designed to be practical for instructors who teach a range of molecular and cellular contexts, so the language is not specific to a single biological mechanism. A scale of 1-5 is used with a degree of flexibility; intermediate scores (2 and 4) are available for instructors to rate explanations that fall between criteria. With this rubric, students know what is expected and they can reflect on their own learning, and instructors might gather information regarding the performance of students and provide concise feedback to guide them.

To exemplify the application of the rubric (Table 4.5), it can be applied to the presented explanations. The expert explanation made by Buck contains all the components to their fullest detail and fully integrates each of the parts into a coherent

whole. Therefore, Buck's explanation would receive M, 5; A, 5; C, 5; H, 5; I, 5. For the pre-intervention explanations about the Phot 1 mechanism (Course II, exam 2, figure 4.3) the score would be M, 1; A, 5; C, 4; H, 5; I, 3. The produced score indicates that the explanation did not show how research *Methods* (M) informed ideas about the mechanism and coherent *Integration* (I) was included for some, but not all of the components, resulting in a 3. The *Context* (C) of the mechanism could be improved to connect to a more detailed context, so this was given a 4. The other components were reasonably clear and thus received 5's. The explanation about ATP Synthase and the electron transport chain (Course III, exam 2, figure 4.5) achieves M, 5; A, 5; C, 5; H, 3; I, 5. While integration and most components were exemplary, the instructor wanted more details of the specific proteins involved in the electron transport chain, which is why the response received a score of 3 for H. These examples serve to demonstrate the potential of the rubric as a useful tool for evaluating student explanation and providing feedback about areas to improve. Such feedback will be instrumental in making the MACH model way of explaining molecular and cellular mechanisms comprehensible to students.

Table 4.5.
Performance rubric for guiding molecular and cellular explanations with MACH.

	Inadequate (1 pt)	**Needs Improvement (3 pts)**[2]	**Exemplary (5 pts)**
Methods	Response does not address how science research *methods* and measurements support ideas about the mechanism or contains major flaws.	Addresses only some minor aspects of how science research *methods* and measurements support ideas about the mechanism and contains minor flaws.	Demonstrates a clear and complete explanation of how science research *methods* and measurements support ideas about the mechanism and contains no flaw.
Analogies	Response does not tell or illustrate an *analogical story* about the mechanism.	Tells or illustrates an inappropriate or incomplete *analogical story* about the mechanism.	Tells or illustrates a clear and coherent *analogical story* about the mechanism.
Context	Response does not address a *context* to show why the mechanism is important or contains major flaws.	Addresses only some minor aspects of a *context* that show why the mechanism is important and contains minor flaws.	Demonstrates a clear and complete *context* to show why the mechanism is important and contains no flaw.
How	Response does not address *how* the mechanism works or contains major flaws.	Addresses only some of the entities, activities, and organization involved in *how* the mechanism works and contains minor flaws.	Demonstrates a clear and complete explanation about *how* the mechanism works by addressing the entities, activities, and organization involved and contains no flaw.
Integration	Response does not *integrate* the above components into a coherent explanation about the mechanism.	*Integrates* only some of the above components into a coherent explanation about the mechanism.	*Integrates* all of the above components into a coherent explanation about the mechanism.

[2]Two points may be given to categorize explanations that fall between *Inadequate* and *Needs improvement* of the respective criteria, or four points, between Need improvement and Adequate. *Needs improvement* may be applied to explanations containing a flaw and may include an incorrect fact, vague information, or other ways to improve

Table 4.6.
Considerations for developing a rubric to guide explanations with the MACH model.

Consideration	**Evaluative questions**	**Addressed in development**
Theoretically consistent	Does the rubric capture the components of an expert explanation?	Alignment of rubric to the integration and quality of MACH components as seen in explanations by biologists.
Usefulness for instruction	Does the rubric provide useful information to educators for teaching and learning?	Consultation with students and instructors to clarify and modify the rubric's language and content.
Discriminating high from low performance	Does the rubric discriminate the quality of the explanations?	Separation of high and low quality explanations by ranking explanations and comparing with rubric scores.

4.6 Discussion

The call to action in this case was the need to provide guidance to both instructors and students so that they may understand and include the components used by biologists when explaining molecular and cellular explanation. To address this need, we asked: How does one help instructors and students understand and include the components biologists use when explaining molecular and cellular mechanisms? We first worked with practicing scientists to see how the MACH model represents specific components to include for skillful explaining, then we transitioned this model into the classroom for teaching by developing a physical model and activity, and we taught students to use the model to analyze, interpret, and construct explanations of molecular and cellular mechanisms. Informed by students' performance and difficulties, the model and instructional activities were modified and we developed a new performance rubric as shown in Table 4.5. In so doing, we developed PCK for explaining molecular and cellular mechanisms in the classroom in a way that fits Shulman's expectations (Shulman, 1986). That is, throughout this series of studies, we included scientists to develop our subject matter knowledge (Trujillo et al., in press), and we worked with students and instructors to make representations of this knowledge comprehensible to students. Finally, we looked carefully at student work to gain knowledge of the aspects difficult for them to learn by analyzing their explanations and interviewing students (Trujillo et al., In preparation), and we applied what we learned about students to further develop instructional resources (Trujillo et al., 2014a), including a physical model (Trujillo et al., 2014b) and a rubric (Table 4.5). Overall, these experiences helped us to develop PCK for explaining molecular and cellular mechanisms in the classroom.

The products reported have limitations since much of the previous research has been exploratory in nature. For instance, the MACH model was developed from interviews with only seven scientists so the findings require further replication and validation before they can be generalized. Likewise, the intervention has had a posi-

tive effect on students in Course II, but these trends may not be maintained when the intervention is used at other universities, over long periods of time, or with a different student body. That said, the rubric, tetrahedral MACH model, and activity have been designed for specific purposes and contexts. Thus, their ability to aid instructors and students beyond our classes is largely unknown. As with many instructional innovations, future research and implementation is needed to understand the efficacy of the resources presented.

In the future, the resources and intervention may be tested in controlled experimental or quasi-experimental studies to isolate important variables that impact student performance, or alternatively, instructors may wish to modify the rubric, distribute the MACH model, or tailor the instructional activities to better suit the needs of other students and courses. Indeed, the MACH model, if adapted appropriately, may help students in high school, community colleges, and other educational institutions. Finally, the MACH model rubric may provide a new research instrument to measure student explanations, but this will require systematic measurements to establish reliability and validation before any claims may be made when using it (American Education Research Association, American Psychological Association, & National Council on Measurement in Education, 1999).

4.6.1 Summary of findings and implications

Pedagogical Content Knowledge (PCK) and useful new instructional resources can be developed for students and instructors by following the logical sequence of four steps we have illustrated here. In brief, first we dedicated careful attention by reviewing relevant literature and interviewing expert scientists to develop a model of the components they include in their explanations. Next, we modified the model to communicate clearly with students for classroom instruction. Then, we implemented a teaching intervention and evaluated its impact by looking carefully at student work and interviewing a range of students. Finally, we modified the resources and created

a performance rubric to show students key differences between high and low quality work. In illustrating this process, we show that the development and use of the MACH model for instruction helped students to include the components in their explanations, but we found a need to help students integrate the components into coherent, well-connected explanations, so we further developed resources to address this need. In alignment with the idea of PCK by Shulman (1986), we show how to build knowledge for teaching upon both subject matter knowledge as represented by the MACH model components and knowledge about difficulties students encounter as they are learning. Although our work has followed four steps, in reality four steps is not enough because other biology instructors may now begin to develop new PCK and instructional support materials appropriate to their own context when the MACH model is implemented in other classrooms, by paying attention to difficulties students encounter when they are learning about science subject matter. Our goal for this paper is also to address the uncertainties of connecting current biology research to teaching and learning. The same four-step research approach can be applied to other science subject matter, for example, host-pathogen coevolution, the development of novel disease models, research with stem cells in physiology and drug discovery, or the development of cancer-targeted microRNA (miRNA) drugs, to name just a few of the current research topics that should soon be brought into the classroom. By providing a general education research method, we hope more teaching will soon align with the practice of biologists, while meeting the needs of diverse students as recommended by the *Vision and Change* report (Brewer & Smith, 2011).

4.7 Acknowledgments

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CHAPTER 5. CONCLUSION

While each manuscript makes an unique scholarly contribution, the dissertation showcases how one can use the modeling process to richly depict a skill of biologists – the ability to explain biological mechanisms – and translate this skill to a teaching and learning context. Chapter 1 introduced the three studies and provided some background for the reader of how the three studies fit together. Chapter 2, the first study, presented the MACH model of the components used by biologists when they create explanations, which was developed from a literature review and an analysis of interviews. Chapter 3, the second study, presented the results of a mixed-methods study of a teaching intervention that used the MACH model in an undergraduate biology classroom. Chapter 4, the third study, reports the pedagogical content knowledge (PCK) gained from the preceding studies and presents instructional innovations developed by applying this knowledge. The purpose of this final chapter is to make explicit the scholarly contributions of this PhD study. Chapter 5 focuses on contributions, significance, limitations, and future directions of the research. As a whole, this work showcases how modeling and design can contribute to theory and inform the practice of teaching, and in so doing, the dissertations improves an understanding of the role of explanations in biology and in the teaching and learning of biology.

5.1 Significance

5.1.1 Contributions of the first study and the MACH model

The MACH model is the largest contribution of the dissertation due to the fact that it was developed in the first study and informed subsequent research. Although

limited to a representation of the sample, the MACH model extends the previous models of mechanistic explanations in biology to represent the essential components found in a range of life scientists' explanations of molecular and cellular mechanisms. The model depicts the four components, which were derived from themes in the explanations made by the participant biologists, and include: *Methods* (M), *Analogy* (A), *Context* (C) and *How* (H).

In addition to the model, the study forwards scholarship in two notable ways. First, a result of the first study was that biologists, when explaining, treat biological entities as if they were actors with purpose, intention, needs and wants. The biologists were using these formulations in conjunction with a full mechanism to tell stories in an analogical manner (A), and as such, a major implication for education research is that the informal language used by students may not be indicative of alternative conceptions that hinder learning, since, in fact, scientists use these as less precise formulations (Zohar & Ginossar, 1998). This finding has implications for those who study learning since it demonstrates that even scientists who can deliver an explanation in full mechanistic detail use language would normally be considered unscientific in nature. Additionally by using *Analogies*, the experts were mixing 'why' explanations with 'how' explanations, which suggests that explanations about cellular and molecular mechanisms are not strictly focused on proximate causes (H) as has been suggested by Mayr (2004). In fact, this first study opens the door to many questions about the uses and limitations of explanations and whether to not it is at all possible to separate a purely mechanistic explanation from other factors of explanation. The results presented suggest that studying explanations about biological mechanism with a holistic view may be beneficial. The MACH model contributes to the theory of explanations by providing a new, more inclusive model of explanation which is based on both a literature review and oral explanations made by practicing biologists.

5.1.2 Contributions of the second study and the teaching intervention

Next, the MACH model served as a representation for explaining in the classroom. We designed a teaching intervention so that students would learn to use the components. The main contributions of this study include an understanding of how undergraduate students in an introductory class explain before and after a teaching intervention, and reasons from students as to why they thought the MACH model was useful. Unlike biologists, before the intervention, many students omitted the M component when explaining. This result was informative because it indicates that novices differ from experts in what components they use to explain. After the teaching intervention, more than 90 percent of students used all of the MACH components, which indicated that the intervention was successful. From interviews with select students, it was found that the MACH model was helpful because students used it to monitor their understanding, to communicate completely and concisely, and to identify gaps in their explanations. While the success of the intervention is a clear contribution to scholarship, the study revealed students fell short of the experts, which is an additional contribution. For instance, Petunia had difficulty learning how to explain with the MACH components in an integrated way and Felix's exhibited difficulty when recognizing and using the M component. Altogether, much was learned from the mixed-method study.

5.1.3 Contributions of the third study, an activity, and a rubric

The third study focuses on the development and application of pedagogical content knowledge (PCK), or subject matter knowledge for teaching, as it relates to teaching biological explanation. Written for an audience of scientists who teach, this report includes what was learned over the three teaching interventions and presents teaching resources as scholarly contributions. This study presents how to bring a scientific skill into the classroom. For us, it began with the development of the MACH model as a representation of the components used by biologists. Next, the MACH

model was converted into a physical tetrahedral model to make a representation of the components comprehensible for students. Then in the course of teaching with MACH, PCK was developed by understanding what aspects of explanation were easy or difficult for learners. Finally, the knowledge for teaching was applied to improve a teaching activity, which emphasized integration to introduce students to the MACH model, and a rubric to evaluate student explanations. These outcomes contribute to the knowledge of molecular and cellular mechanisms for explaining in the classroom, and in so doing, the findings will allow others to replicate our work and further the development of teaching resources.

5.2 The big picture

This dissertation fits within a bigger picture of science education because, like most science education documents, it seeks to make the teaching and learning of science congruent with the science practices. As such, this dissertation strives to bring a scientific skill, namely, the ability to explain molecular and cellular mechanisms, into the teaching and learning of biology to establish congruence in biology education. To be effective in a traditional sense, science education must reflect the practices of science and teachers are expected to help students develop an epistemology of science which includes the knowledge, practices and ways of knowing in science (Russ, 2014). It is assumed that if we teach in a manner that is not informed by science knowledge, our students might learn skills that are incongruent with science.

Figure 5.1 is simple model, a triangle of congruence in science education, to illustrate the connections between science, teaching, and learning and to provide a useful visual for reflecting on the issues encountered during the studies and the larger contribution of the dissertation. The triangle model has three corners to serve as representations. The practice of science is at the top corner of the triangle, the learning of science is at the right corner, and the teaching of science at the left corner.

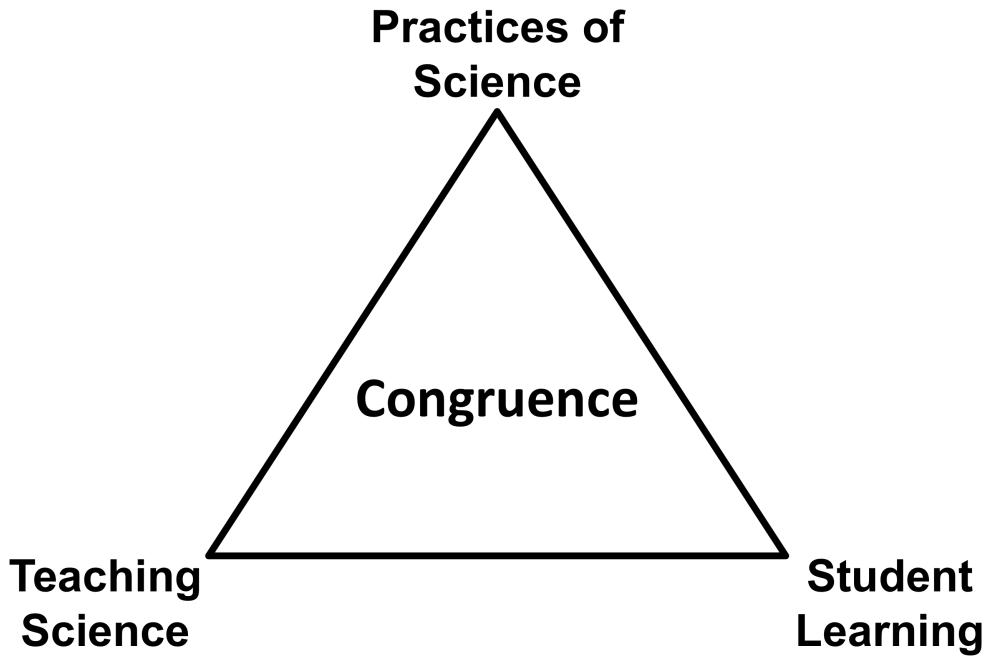

Fig. 5.1. A triangle model depicting the congruence of science education.

Related to the top corner, science education depends on a knowledge of science including the practices, knowledge, and ways of knowing in science. Before attempting to bring science into the classroom, one must understand science. There was incongruence among the models of explanations represented in the education literature and this provided a rationale to study what biologists include when they create explanations about mechanisms. The produced MACH model permitted a valid representation of explanation that would help to establish congruence.

Next, an understanding of student learning exists on the right corner of the triangle. Students are expected to develop skills, knowledge and habits of mind of science, so it is important to consider what knowledge students bring to the science classroom and what knowledge students develop during the instruction. Related by an incongruence on the right side, previous research claims that students face difficulties when explaining and in our study, students lacked the M component, so the MACH model was used as a teaching intervention to help students to explain as scientists explain. The results proved useful; students explained in a way that was congruent with biologists, but a few new issues of congruence were raised, such as students failing to integrate the components.

The third corner, the teaching of science, relates to the practices of teachers, resources, and curriculum used to teach science. As previously, mentioned, it is the duty of the teacher to bring the knowledge of science into the classroom so that students may develop an epistemology of science. To address such, the teacher must know both the science and student learning for teaching – or PCK, which channels the left side and bottom side of the triangle into knowledge for teaching. Along the bottom side, we found that the intervention helped students to use the MACH components and develop explanations as biologists would, but some students had difficulty integrating the components. As such, the teaching intervention activity was modified and a rubric was designed to integrate the knowledge of students' performance and the knowledge of the biologists explanations to better teach. The activity, tetrahedral version of the MACH model, and rubric target integration. In so doing, they help

to establish congruence between science knowledge, students learning, and teaching with the MACH model.

For science education to be effective, all three corners must be in agreement, and should any incongruence be found, then these must be addressed or else there is a risk that students may be trained in ways that do not prepare them as scientists. By agreement, I mean that the epistemologies of the science classroom are consistent with the epistemologies of science. For instance, if a teacher misunderstands the practices or knowledge of science, misrepresents these when teaching, or misjudges student learning of science, there will be less agreement between the the three corners. However, there is disagreement about the extent that science education should mimic the practices of science and other epistemologies for teaching and learning may be appropriate (Russ, 2014). By recognizing that not all students in science course are preparing to be practicing scientists, a consideration of other models of science education is important and necessary. While the triangle model could be rigorously developed, it is beyond the scope of this research. The congruence model serves to draw connections for the reader to indicate how the work advanced by reducing harmful incongruence and improving upon strengths across the three studies for biology education. By no means have we perfected the teaching of mechanistic explanations in undergraduate biology, but the dissertation has achieved a larger purpose, which was to contribute to the scholarship of research and teaching of biological explanations. By focusing on establishing congruence, we have produced a model of the explanations made by biologists and designed interventions, activities, resources, and rubrics for teaching students to explain.

5.3 Critical analysis

5.3.1 Major limitations

While the presented findings, models, and resources make scholarly contributions, there are many limitations associated with these. First and foremost, the

MACH model is limited because it is based on a small set of biologists, which excluded many sub-disciplines, and was produced from thematic analysis, which may overlook important features of explanations. The limitation of the sample is partly due to the scope of the purpose of modeling and partly due to the sampling. For instance, the evolutionary biologists were excluded because it was assumed they do not work with cellular and molecular mechanism. Had I investigated the 'Why' questions that biologists ask instead of the 'How' questions, my research would have driven me to understand ultimate causal explanations related to evolutionary theories (Mayr, 2004). However, not all fields that work with mechanisms were included. For instance, plant biologists were excluded even though they do work on such systems. As such, the model will need to be tested against a larger sample of scientists to make broad claims about the MACH model's power to capture all types of biological explanations. In addition to the sampling, analysis is another source of variation.

Thematic analysis focused on identifying patterns across the interviews. As a limitation, this analysis overlooks the aspects which are unique to individual scientists or to sub-disciplines. For instance, biochemists may explain in an unique way that is different than other life scientists and would extend the MACH components if modeled. These patterns may also be important for understanding what makes a neuroscience, biochemistry, or physiology explanations unique, but would require a different set of methods than those reported here. For instance, it remains unknown if developmental biologists includes components in their explanations about mechanism that may differ from those of scientists in other sub-disciplines. By appropriate sampling and by performing an analysis with constant comparison or contrasting cases, research may lead to new insights about explanations.

Any study of explanations faces limitations related to the modality, the audience and the prompts to elicit an explanation. First, one major limitation is that the MACH model is informed by oral explanations made by scientists. The modality of the explanation may affect the contents of the explanations. Written explanations made by the same scientists may have different components once modeled. The

oral explanations were audio recorded so non-verbal communication, such as gestures, could not be analyzed, and this may have omitted important patterns. Second, explanations are rooted in communication and tend to be constructed by the explainer with an audience in mind. As such, there is a need to better understand how the intended audience affects the content of explanations. For example, Felix said he would not use the MACH model to explain to small children but would for his peers. The factor of audience was not made explicit with students and may have affected the results observed in the intervention. Finally, a variety of prompts were used throughout the studies in exams, worksheets, and oral interviews, which varied in their specificity and context. For instance, the oral interviews elicited scientists and students to explain a mechanism of their choice, whereas an exam prompt in the third class asked students to explain a mechanism to connect electron transport to ATP synthase. A limitation of studying explanations is that prompts may cue explainers to use certain MACH components, that is exam prompts frequently provide a context to elicit an explanation relevant to the course, but this, in turn, may affect the results. Throughout the studies, we have tried to manage these limitations, but these issues may be inherent in any study of explanation.

Finally, the teaching resources and student results have limitation. Design of the activities and the rubric occurred with many drafts and iterations that were informed by our experience as instructors and researchers. As such, the usefulness of these resources is currently limited to our institutional setting and students, and the resources and intervention may not have such an impact outside of the educational context in which they were designed. Additionally, the long term impact of the intervention on the students is unknown. It may be that students used the MACH components to address the exam prompts which asked students to explain with MACH, but the students may have resorted to old habits once the course was finished. Thus, the degree to which students have internalized the MACH model as part of their natural explanation remains unknown. These limitations and gaps provide motivation for further investigations with the MACH model.

5.3.2 Future directions

Future research may address the above-mentioned limitations or extend the current research and teaching to produce new contributions. Since the MACH model was developed with a small set of biologists, future research may seek to include a larger sample of scientists. For instance, analogous models of the MACH model may be appropriate for representing explanations made by chemists, a wide range of biologists, or other sciences. Future research may look for additional modalities and sources of explanations, such as press releases, presentations, animations, and podcasts, so that the MACH model may be validated, modified or extended to address explanations in a range of modalities. A major challenge of studying explanations made by biologists will be managing the variation produced across individuals and across sub-disciplines. Given, the large amount of variation known to occur from contexts, disciplines, areas of special expertise, audience, modality, individual style, and other common sources, there is a need to sample carefully and use purposeful analysis and data processing. Then by addressing these factors systematically, one may be able to pinpoint unique components that transcend other factors. For instance, A study of explanations made by scientists in a specific sub-disciplines may produce fruitful results of unique aspects overlooked by the thematic analysis of several discipline. Working with scientists will help improve the the MACH model as a representation of explanations in the sciences.

In terms of research with students, future inquires may focus on extending the current work. For instance, controlling factors, such as modality, audience, and prompts, as part of an experimental approach, may reveal the variables that affect the creation of a quality explanation. Conversely, naturalistic studies of student explanations may use MACH as an analytical framework to reveal insights into how students develop an expertise for explaining without a teaching intervention. Finally, researchers may wish to replicate the results of the intervention in other educational contexts, such as other institutions, students, instructors and topics. Replication of

the second study would help determine the generalizability of the previous findings and further modifications to the intervention may extend efforts to teach students to explain. From my experience, future research will benefit from involving both the instructors and students to forward the teaching intervention.

For teachers, the activity and tetrahedral model are available to use, modify and adapt in other biology classrooms (Trujillo, Anderson, & Pelaez, 2014a, 2014b). Educators may use these to teach students to explain, or use these resources as a model to create and design additional teaching resources, rubrics, and models for teaching science. Provided that teachers find the MACH model and associated resources both practical and useful for teaching, there is potential for the use of the model to grow in scale. Scaling up may help many students to develop the skill of explaining biological mechanisms. Additionally, beyond the classroom, the MACH model may be a tool useful for designing informal education settings, such as museums, electronic resources, and interactive applications, as well as for scientific communication, such as journalism, dissemination of research, and structure of grant application. For instance, scientists may use the tool to ensure they communicate effectively the essential parts of their work to the public or to grant committees. Alternatively, journalists may be able to better communicate the research methods that inform ground-breaking research or limit the context of grandiose claims. MACH may provide a standard for communication beyond explanations in the classroom.

Ultimately, the future work in the field of teaching and learning biological mechanisms will depend on the efforts of many researchers, scientists, teachers, and students working in tandem.

5.4 Conclusion

The impact of the MACH model is perhaps best evaluated by its ability to help individuals communicate outside of a classroom setting. As such, I was touched

when I read response from a student in the biochemistry course for health science majors:

> *Explain by means of one specific example how you would use the knowledge you gained from this course to enhance your practice as a health professional or any other career you intend to pursue.*
>
> Student: I am a pre-physician's assistant major. [...] One thing I found very informative was the discussion of the MACH model to explain cases. This is a technique of explaining a topic in as much well-rounded detail as possible. You use the technique by going through the methods of studying the subject, analogies (whether words relating the topic to an easy to understand subject or pictures), context or what it means for the individuals you're talking about or where the topic or process is located and finally [how] the topic's system works. This is very important and I will be using it to explain to my future patients what their specific disease is and give them all the details they want. By using this I know I will not leave any information out. By understanding the biochemistry of the subject or disease, I will also be able to fully explain the How portion. (Course III, final exam prompt)

This excerpt, while anecdotal in nature, reminds me of the significance of the MACH model. The MACH model empowers students, scientists, and teachers to communicate effectively about biological mechanism. As mentioned in the introduction, I first encountered the power of an appropriate explanation at age fourteen when I helped an oncologist, using an analogy of a jammed bicycle, explain to my father how chemotherapy was eradicating his leukemia. Now, after developing the MACH model and having taught with it several times, I have helped students to understand the components our participant experts use to explain molecular and cellular mechanisms and produced resources for teachers to help additional students to understand explanations, and these students will go on to become scientists, workers, informed citizens, and, perhaps, oncologists.

5.5 References

Mayr, E. (2004). *What makes biology unique? considerations on the autonomy of a scientific discipline*. Cambridge, UK ; New York, NY: Cambridge University Press.

Russ, R. S. (2014). Epistemology of science vs. epistemology for science. *Science Education*, *98*(3), 388–396.

Trujillo, C. M., Anderson, T. R., & Pelaez, N. J. (2014a). An activity aimed at improving student explanations of biological mechanisms. In *Piberg instructional innovation materials.* `http://docs.lib.purdue.edu/pibergiim/2`: West Lafayette, IN: Purdue University.

Trujillo, C. M., Anderson, T. R., & Pelaez, N. J. (2014b). A tetrahedral version of the mach model for explaining biological mechanisms. In *Piberg instructional innovation materials.* `http://docs.lib.purdue.edu/pibergiim/1`: West Lafayette, IN: Purdue University.

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APPENDICES

APPENDIX A. AN ACTIVITY AIMED AT IMPROVING STUDENT EXPLANATIONS OF BIOLOGICAL MECHANISMS

Authors: Caleb M. Trujillo,Trevor R. Anderson, and Nancy J. Pelaez

This document is intended for use by instructors and their students. The activity contains steps to introduce students to the MACH model involving analyzing and discussing explanations about biological mechanisms. Initially, students read modified articles about biological mechanisms during class, although instructors may prefer to assign readings outside of class before the activity. During the activity, students are required to analyze the readings for evidence of research methods, analogies, context, and mechanisms. In so doing, students learn how to integrate the information pertaining to each of the MACH model components into a coherent explanation about their biological mechanism. After performing the above activities individually, students discuss findings in pairs, and then share their ideas with the class. After discussion, the instructor presents the MACH model. In our experience once the above activity has been successfully completed, students show strong evidence of competence in the writing of explanations about mechanisms. Details of the tetrahedral MACH model, and its related class activities, are freely available in the Purdue International Biology Education Research Group (PIBERG) ePubs collection. Together with the description of the activity, we have included advice on suggested topics, citations of suggested readings, and examples of typical student analyses of such readings.

Trujillo, C. M., Anderson, T. R., & Pelaez, N. J. (2014). An activity aimed at improving student explanations of biological mechanisms. In *Piberg instructional innovation materials*. http://docs.lib.purdue.edu/pibergiim/2: West Lafayette, IN: Purdue University.

An Activity Aimed at Improving Student Explanations of Biological Mechanisms

Created by Caleb M. Trujillo, Trevor R. Anderson, and Nancy J. Pelaez
Purdue University
[*Note to instructors: Edit bracketed sections*]
Modified by [*Your name, your institute, and the date*]

Read

Individually, read the biological explanation provided.

[*Approx. 5-10 minutes. Instructors may prefer to assign the reading for outside of class. Instructors may provide readings about any topic with an explanation about a biological mechanism or encourage students to find one of their own choice. Previously we have used topics of cystic fibrosis transmembrane conductance regulator, vesicle trafficking, aquaporin and ion channels functions. We modified readings such as the following to create one-page handouts:*

Skwarecki, B. (2014). Cystic Fibrosis Might Be 2 Diseases. *Scientific America.* http://www.scientificamerican.com/article/cystic-fibrosis-might-be-2-diseases/

Trivedi, B. P. (2013). Doorway to a Cure for Cystic Fibrosis. *Discover. http://discovermagazine.com/2013/september/14-doorway-to-a-cure*

von Heijne, G. (2003). Advanced information on the Nobel Prize in Chemistry. *Nobelprize.org*. http://www.nobelprize.org/nobel_prizes/chemistry/laureates/2003/advanced-chemistryprize2003.pdf.]

Zierath, J. R. & Lendahl, U. (2013). Machinery Regulating Vesicle Traffic, A Major Transport System in our Cells. *Nobelprize.org* http://www.nobelprize.org/nobel_prizes/medicine/laureates/2013/advanced-medicineprize2013.pdf]

Think

What components does the author integrate into their explanation? Analyze and mark the text with the respective shapes as follows:

- Science research methods (■);
- Models, figures, graphs, or analogies including anthropomorphic stories (▲);
- Biological and/or social contexts (★);
- How the phenomenon works through physical causes (●); and
- Places where the above components blend and interweave (✓).

Be prepared to share with a partner your thoughts about how the author integrates these components into a coherent explanation.

[*Approx. 5 minutes. Examples from the text are shown on next page for instructors.*]

Pair

With a partner, come to consensus about what components the author did and did not include in the explanation. Share what you noted about the passage. Be sure to discuss any missing items from the above list and address how well the author blended the components in the explanation.

[*Approx. 5 minutes.]*

Share

Report the ideas you discussed with your partner to the class.

[*Approx. 5 minutes.]*

Learn

Learn from your classmates and the summary by the instructor.

[After the activity, we distribute the tetrahedral MACH model and teach students to use the MACH model. The tetrahedral MACH model can be found at the Purdue International Biology Education Research Group (PIBERG) ePubs collection (https://www.bio.purdue.edu/piberg/).]

For contributions, the authors would like to acknowledge the Visualization in Biochemistry Education (VIBE) group, John Alaniz, Kamali N. Sripathi, and Sara L. Johnson.

Examples of the MACH components found in the assigned text.

Component	Examples from Skwareck (2014) on the topic of cystic fibrosis transmembrane conductance regulator (CFTR).	Analysis of example
M	"Whitcomb's team screened a group of nearly 1,000 patients with pancreatitis and found nine abnormal but supposedly harmless versions of the CFTR gene."	References how scientists sampled patients for data.
	"The techniques the researchers used to figure out the details of how each mutation changes the protein are 'extremely challenging' and 'kind of an art form,' "	Reports about the research methods.
	"Different diseases that all look the same on CAT scans."	References to tools and data collected.
	"Computer simulations confirmed..."	Uses modeling software of investigate.
A	Figure: [http://discovermagazine.com/~/media/Images/Issues/2013/September/gene-mutations-in-CF.jpg?mw=900]	Displays a cartoon model of a protein.
	"Seemingly benign mutations break the switch that turns CFTR from a chloride portal to a channel for bicarbonate."	Uses of a switch as an analogy.
	"CFTR leads a double life."	Anthropomorphizes the entity.
C	"The hereditary disease affects 30,000 Americans, and patients die unless they receive treatment to clear their lungs."	Includes a social context; the disease affects the lives of many people.
	"They can suffer from painful pancreatitis, as well as sinusitis and, in men, infertility."	Includes a biological context; many organ systems are affected.
H	"Cystic fibrosis results from mutations in a gene that produces a tube-shaped protein known as CFTR, essential to the balance of electrolytes in the body. Specifically, this protein allows chloride ions to pass in and out of cells."	Includes specific entities (proteins and ions) interact with spatial and temporal organization.
	"Whitcomb's eventual goal is to disentangle the distinct causes of what, until recently, appeared to be a single disease."	Focuses on the causes of the disease(s).

Examples of the MACH components found in the assigned text (Cont'd).

Component	Examples from Trivedi (2013) on the topic of cystic fibrosis transmembrane conductance regulator (CFTR).	Analysis of example
M	"Tsui had read about a technique for locating a desired gene through DNA markers present in sick people but absent in healthy ones." *	References the research methods.
	"They added a chemical called genistein, a known door-opening drug that, unfortunately, was so weak it worked only in the test tube. Finally, a robotic eye scanned each mixture. If cells were unaffected, the dye caused them to glow orange."	Includes a technique used in drug discovery to visualize channel activity.
A	Figure: [http://discovermagazine.com/~/media/Images/Issues/2013/September/gene-mutations-in-CF.jpg?mw=900]	Includes diagrams of disease and non-disease states.
	"The protein was shaped like a tube and wedged in the outer surface of the cells, resembling the kind of biological valve that would move chloride in and out."	Uses shapes, wedges, and valves as analogies.
	"Instead, the defective protein remains stuck inside the cell, like a Cheerio trapped in a balloon."	Uses macroscopic objects as analogies.
C	"Laura and Cate are among thousands of Americans who have cystic fibrosis"	Includes social context; CF affects personal lives.
	"Affecting one in every 3,900 births in the U.S., CF is one of the most common genetic disorders known."	Includes social context, the disease.
H	"A CFTR protein with this mutation cannot fold properly and cannot navigate its way to the surface of the cell where it would normally reside, providing a channel for chloride to flow in and out."	Explains disease state by the properties of the protein and its spatial organization.
	"Riordan was an expert on proteins called ABC transporters, molecular elevators that shuttle things like fats, drugs and other molecules back and forth across cell membranes."	Addresses spatial organization and activity of the transporter.
	"A mutated gene that produced a broken protein involved in chloride flow could cause a salt imbalance and all the devastation observed."	References how physical entities prevent the activity of chloride channels.

* The modified version of the article used during a Fall 2014 course had all excerpts of research methods (M) removed such that students could contrast articles with and without research methods.

Examples of the MACH components found in the assigned text (Cont'd).

Component	Examples from Zierath and Lendahl (2013) on the topic of vesicle trafficking.	Analysis of example
M	"To test the SNARE hypothesis, Rothman used an *in vitro* reconstitution assay and revealed that SNAREs could indeed fuse membranes."	References specific methods used by scientists.
	"He used temperature-sensitive mutants and screened for genes affecting the intracellular accumulation of secretory enzymes."	Includes screening, a specific technique used in research.
A	Figures [http://www.nobelprize.org/nobel_prizes/medicine/laureates/2013/advanced-medicineprize2013.pdf]	Indicates cartoon models of vesicles.
	"The vesicle fuse at the right location and that cargo molecules are delivered to the correct destination."	Tells a story as if vesicles have an end goal.
C	"…For example, metabolic disorders such as type 2 diabetes are characterized by defects in both insulin secretion from pancreatic beta-cells and insulin-mediated glucose transporter translocation in skeletal muscle and adipose tissue…"	Makes connections to a disease, a social context.
	"This is the case for example for neurotransmitter release in the brain and for insulin secretion from the endocrine pancreas."	Includes a biological context; compares different functions of the mechanism.
H	"…target and vesicle SNAREs (t-SNAREs and v-SNAREs) were critical for vesicle fusion through a set of sequential steps of synaptic docking, activation, and fusion."	References entities like SNAREs, their activities and how they are organized.
	"…rapid exocytosis of synaptic vesicles, which is under tight temporal control and regulated by the changes in the cytoplasmic free calcium concentration…"	Considers exocytosis as an activity and temporal organization.

Examples of the MACH components found in the assigned text (Cont'd).

Component	Examples from von Heijne (2003) on the topic of aquaporins and ion channels.	Analysis of example
M	"Shortly thereafter, Agre proved this conclusively by demonstrating that expression of CHIP28 in *Xenopus* oocytes made the cells swell rapidly when placed in a hypo-osmotic medium"	References experiment and observation.
	"In 2000 and 2001, the first high-resolution 3D structures of AQP1 and a related glycerol-selective bacterial channel protein (GlpF) were reported"	Includes structural research.
A	Figures [http://www.nobelprize.org/nobel_prizes/chemistry/laureates/2003/advanced-chemistryprize2003.pdf]	Shows models of experiments and channels.
	"Based on these structures, detailed models have been put forward to explain the high permeation rate…"	Indicates models used for explanation.
C	"Aquaporin-like proteins have since been found throughout the living world; in humans alone, there are at least 11 different aquaporin-like proteins, many of which have been linked to various diseases."	Connects to disease, a social context.
	"Plants have an even higher number of aquaporins, with no less than 35 different versions found in the model plant *Arabidopsis thaliana*."	Includes biological context; comparing to other domains.
	"The cloning and overexpression of a bacterial K+ channel with high homology to eukaryotic K+ channels (Schrempf et al., 1995) suggested to some workers that prokaryotic channels might finally provide the missing key to structural studies of ion channels."	Indicates channels of different organisms of varying biological contexts.
H	"The local electrostatic field generated by the protein switches polarity in the middle of the channel, forcing the passing water molecules to rotate in such a way that their dipole moments are oriented in opposite directions in the upper and the lower halves of the channel."	References entities, their interactions and organization.
	"A comparison of the KcsA and MthK structures suggested a general mechanism for channel gating, in which a conformational change in the sensor domain pulls the transmembrane helices apart near the intracellular end of the channel."	Includes entities changed states through conformational changes.
	"Some K+ channels conduct ions in only one direction, serving as 'molecular diodes'. Such inward rectifying channels are blocked by Mg2+ and polyamines that penetrate into the channel from its cytosolic end when the membrane is depolarized."	Addresses the entities, the activity (or lack of activity when 'blocked'), and the state of the membrane.

Work cited:

Skwarecki, B. (2014). Cystic Fibrosis Might Be 2 Diseases. *Scientific America.* http://www.scientificamerican.com/article/cystic-fibrosis-might-be-2-diseases/

Trivedi, B. P. (2013). Doorway to a Cure for Cystic Fibrosis. *Discover*. http://discovermagazine.com/2013/september/14-doorway-to-a-cure

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Zierath, J. R. & Lendahl, U. (2013). Machinery Regulating Vesicle Traffic, A Major Transport System in our Cells. *Nobelprize.org.* http://www.nobelprize.org/nobel_prizes/medicine/laureates/2013/advanced-medicineprize2013.pdf

APPENDIX B. A TETRAHEDRAL VERSION OF THE MACH MODEL FOR EXPLAINING BIOLOGICAL MECHANISM

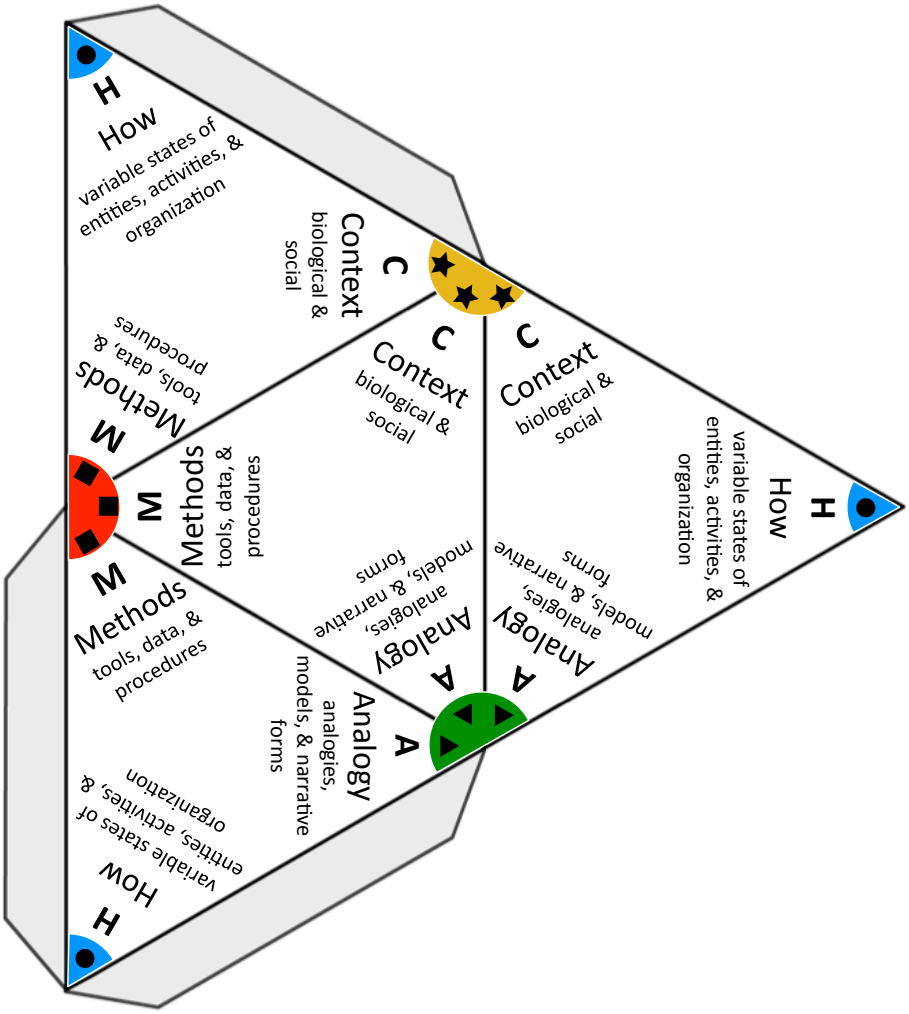
Authors: Caleb M. Trujillo, Trevor R. Anderson, and Nancy J. Pelaez

This document is intended for both instructors and students. Modified from the original MACH model this version, once cut and folded, creates a tetrahedral model that can conveniently be used as a teaching and learning tool to inform and guide students on how to write expert quality explanations of biological mechanisms. Each vertex of the tetrahedron represents a component of the model namely, Methods, Analogy, Context, and How. For a coherent and complete explanation about molecular mechanisms, it is important to integrate information pertaining to all four components of the model. The tetrahedral MACH model has been tested in both undergraduate biology and biochemistry courses and is recommended for use by both practitioners and students in the life sciences. Details of its use as a classroom activity can be found in the Purdue International Biology Education Research Group (PIBERG) ePubs collection.

Trujillo, C. M., Anderson, T. R., & Pelaez, N. J. (2014). A tetrahedral version of the mach model for explaining biological mechanisms. In *Piberg instructional innovation materials*. http://docs.lib.purdue.edu/pibergiim/1: West Lafayette, IN: Purdue University.

A Tetrahedral Version of the MACH Model for Explaining Biological Mechanisms

Created by Caleb M. Trujillo, Trevor R. Anderson, and Nancy J. Pelaez



For contributions, the authors would like to acknowledge the Visualization in Biochemistry Education (VIBE) group, the Purdue International Biology Education Research Group (PIBERG), and the students. A Tetrahedral Version of the MACH Model for Explaining Biological Mechanisms by Caleb M. Trujillo, Trevor R. Anderson, and Nancy J. Pelaez is licensed under Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License, which means it may be modified so long as the authors are acknowledged and as long as others share alike. The diagram can be found at the PIBERG ePubs collection (https://www.bio.purdue.edu/piberg/).

APPENDIX C. CONSENT FORMS APPROVED BY INSTITUTIONAL REVIEW BOARD

All research was performed under the approval of the Institutional Review Board of Purdue University. Protocol numbers are 120301239 and 1306013717. Consent forms were used for study 120301239. Study 1306013717 was deemed exempt.

RESEARCH INTERVIEW FACULTY PARTICIPANT CONSENT FORM
Explanations of Molecular and Cellular Mechanisms

Nancy Pelaez, Associate Professor
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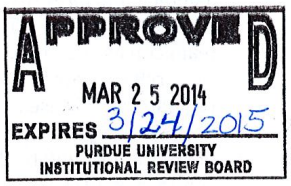

Purpose of Research

The purpose of this study is to investigate the characteristics of explanations about biological phenomena, specifically cellular and molecular mechanisms.

Specific Procedures to be Used

During this research study you will be interviewed individually about:

1. Biological phenomena, and
2. Characteristics of cellular and molecular mechanisms

During the interview, a visual representation will be presented for you to describe, you will reflect on the presented image, and you will have opportunities to draw. This interview will be audio recorded using a digital audio recorder, drawings created during the interview will be collected, and the interviewer will take written notes.

Duration of Participation

The one-on-one interview lasts approximately 45 minutes.

Benefits to the Individual

There are no direct benefits to you by participating in this study. However, the researchers believe that results of the study may hold important benefits for you, other scientists and science educators. These benefits include improvements in curriculum, teaching and learning in biology.

Risks to the Individual

No study is without risk. The risks are no more than you would encounter in everyday life. Breech of confidentiality is a risk; this project addresses this risk by using pseudonyms and codes instead of real names and securing material to be analyzed in locked locations and locked cabinets (see below).

Compensation

No compensation will be offered for this interview.

_____Initials
_____Date

Confidentiality

All audio data and transcripts will be stored digitally and password-protected on a detachable hard-drive which will be in a locked filing cabinet at Purdue University supervised by Caleb Trujillo. General access to the data is restricted to the research team consisting of Dr. Nancy Pelaez and Caleb Trujillo. Additionally, the project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight. Steps will be taken to maintain confidentiality; we use pseudonyms and codes to de-identify data. All data not used for publications or presentations will be destroyed three years after the completion of the project in the summer of 2015.

Voluntary Nature of Participation

You do not have to participate in this research project. Participation or nonparticipation will not affect their standing in the department. If you agree to participate you can withdraw your participation at any time. No negative consequences are associated with your withdrawal.

Contact Information:

If you have any questions about this research project, you can contact Dr. Nancy Pelaez (765-496-3261). If you have concerns about the treatment of research participants, you can contact the Committee on the Use of Human Research Subjects at Purdue University, Ernest C. Young Hall, 10th Floor- Room 1032, 155 S. Grant Street, West Lafayette, IN 47907-2114. The phone number for the Committee's secretary is (765) 494-5942. The email address is irb@purdue.edu.

Documentation of Informed Consent:

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research project and my questions have been answered. I am prepared to participate in the research project described above. I will receive a copy of this consent form after I sign it.

_____ _____

Faculty Participant's Signature Date

_____ _____

Faculty Participant's Name Initials

_____ _____

Researcher's Signature Date

*** Please make sure that you have initialed and dated the bottom of the first page.*

RESEARCH INTERVIEW STUDENT PARTICIPANT CONSENT FORM

Explanations of Molecular and Cellular Mechanisms

Nancy Pelaez, Associate Professor
Caleb Trujillo, Research Assistant
Biological Sciences, Purdue University

Franziska Lang, Research Assistant
Chemistry, Purdue University

Purpose of Research

The purpose of this study is to investigate the characteristics of explanations about biological phenomena, specifically cellular and molecular mechanisms.

Specific Procedures to be Used

During this research study you will be interviewed individually about:

1. Biological phenomena, and
2. Characteristics of cellular and molecular mechanisms

During the interview, a visual representation will be presented for you to describe, you will reflect on the presented image, and you will have opportunities to draw. This interview will be audio recorded using a digital audio recorder, drawings created during the interview will be collected, and the interviewer will take written notes.

Duration of Participation

The one-on-one interview lasts approximately 45 minutes.

Benefits to the Individual

There are no direct benefits to you by participating in this study. However, the researchers believe that results of the study may hold important benefits for you, scientists and science educators. These benefits include improvements in curriculum, teaching and learning in biology. .

Risks to the Individual

No study is without risk. The risks are no more than you would encounter in everyday life. Breech of confidentiality is a risk; this project addresses this risk by using pseudonyms and codes instead of real names and securing material to be analyzed in locked locations and locked cabinets (see below).

Compensation

Students who complete the full interview will receive the $15 dollar gift certificates to Amazon.com. For students who withdrawal from the study before the interview is complete, these individuals will receive the same gift certificates provided they have spent a minimum of 20 minutes in the interview. We will not offer compensation to students who withdraw before 20 minutes.

_____Initials
_____Date

Confidentiality

All audio data and transcripts will be stored digitally and password-protected on a detachable hard-drive which will be in a locked filing cabinet at Purdue University supervised by Caleb Trujillo. General access to the data is restricted to the research team consisting of Dr. Nancy Pelaez and Caleb Trujillo. Additionally, the project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight. Steps will be taken to maintain confidentiality; we use pseudonyms and codes to de-identify data. All data not used for publications or presentations will be destroyed three years after the completion of the project in the summer of 2015. Your name will be given to the business office to collect compensation.

Voluntary Nature of Participation

You do not have to participate in this research project. Participation or nonparticipation will not affect your standing in the university or class. If you agree to participate you can withdraw your participation at any time. No negative consequences are associated with your withdrawal.

Contact Information:

If you have any questions about this research project, you can contact Dr. Nancy Pelaez (765-496-3261). If you have concerns about the treatment of research participants, you can contact the Committee on the Use of Human Research Subjects at Purdue University, Ernest C. Young Hall, 10th Floor- Room 1032, 155 S. Grant Street, West Lafayette, IN 47907-2114. The phone number for the Committee's secretary is (765) 494-5942. The email address is irb@purdue.edu.

Documentation of Informed Consent:

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research project and my questions have been answered. I am prepared to participate in the research project described above. I will receive a copy of this consent form after I sign it.

_____ _____

Student Participant's Signature Date

_____ _____

Student Participant's Name Initials

_____ _____

Researcher's Signature Date

*** Please make sure that you have initialed and dated the bottom of the first page.*

VITA

VITA

Caleb M. Trujillo

EDUCATION

Ph.D., Biological Sciences — May 2015
Purdue University, West Lafayette, IN

B.A., Molecular, Cellular, and Developmental Biology (MCDB) — May 2009
University of Colorado, Boulder, CO

EXPERIENCE IN SCIENCE LEARNING & EDUCATION RESEARCH

Research Assistant — 2011 – 2013
Purdue University, West Lafayette, IN — College of Science
Support professional development of elementary educators through reform of curricular materials, science note booking, and inquiry practices. Research impact on science teaching self-efficacy.

Professional Research Assistant — 2009 – 2010
Carl Weiman Science Education Initiative — MCDB Department
University of Colorado, Boulder, CO
Assessment development and analysis. Student interviews. Observations of instructional use of electronic response system.

Temporary Research Assistant 2009 – 2010
BeSocratic project MCDB Department
University of Colorado, Boulder, CO
Analyze student visualizations of gene regulatory networks. Develop graphing tutorial as an intervention.

FUNDED PROJECTS

Metropolitan School District Washington Township: Using Science as the 'Bonding Agent' to Inquiry and Global Awareness. 2011 – 2013
Math Science Partnership Award. Eichinger (PI), Hart and Walker (Co PIs) $335,670
Indiana Department of Education

Chemistry and the Logic of Life: A Research-Based, Integrated General Chemistry Curriculum. 2008 – 2013
NSF Award to Cooper (PI) and Klymkowsky (Co PI) $499,847.00
CCLI-2 NSF- DUE 0816692

SocraticGraphs: A Free-form Interactive Graphical Recognition System. 2011 – 2014
NSF Award to Cooper (PI), Parkas, Klymkowsky, and Potvin (Co Pis) $196,103.00
NSF TUES NSF- DUE 1043707

CU Science Education Initiative (SEI). 2005 – 2010
Weiman (Founder) and Wood (MCDB department) $5,000,000.00
University of Colorado

RESEARCH PUBLICATIONS

- Trujillo, C.M., Anderson, T.R., & Pelaez, N.J. (In press). A model of how different biology experts explain molecular and cellular mechanisms. *CBE- Life Science Education.*
- Trujillo, C.M., Anderson, T.R., & Pelaez, N.J. (In prep.). Research to practice: Helping undergraduate students explain molecular and cellular mechanisms with the MACH model.

- Trujillo, C.M., Anderson, T.R., & Pelaez, N.J. (In prep.). Discovering pedagogical content knowledge (PCK) to help students understand how molecular and cellular mechanisms are explained.
- Trujillo, C. & Walker, W. (In prep.). Teaching efficacy of elementary science educators and the influence of professional development - A mixed-methods approach.
- Perez, K. E., Hiatt, A., Davis, G. K., Trujillo, C., French, D.P., Terry, M., & Price, R. M. (2013). The EvoDevoCI: A concept inventory for gauging students' understanding of evolutionary developmental biology. *CBE-Life Science Education, 12*(4), 665-675.
- Hiatt, A., Davis, G. K., Trujillo, C., Terry, M., French, D. P., Price, R. M., & Perez, K. E. (2013). Getting to Evo-Devo: Concepts and challenges for students learning evolutionary developmental biology. *CBE-Life Science Education, 12*(3), 494-508.
- Zhang, Y., Yang, Y., Trujillo C., Zhong, W., & Leung, Y.F. (2012). The expression of irx7 in the inner nuclear layer of zebrafish retina is essential for a proper retinal development and lamination. *PloS ONE, 7*(4): e36145.
- Trujillo, C., Cooper, M.M., & Klymkowsky, M.W. (2012). Using graph-based assessments within Socratic tutorials to reveal and refine students' analytical thinking about molecular networks. *Biochemistry and Molecular Biology Education, 40*(2): 100-107.
- Smith, M. K., Trujillo, C. & Su, T.T. (2010). Benefits of using clickers in small-enrollment seminar-style biology courses. *CBE-Life Science Education, 10*(1): 14-17.

INSTRUCTIONAL INNOVATIONS PUBLICATIONS

- Trujillo, C.M., Anderson, T.R., & Pelaez, N.J. (2014). An activity aimed at improving student explanations of biological mechanisms. *PIBERG Instructional Innovation Materials*. http://docs.lib.purdue.edu/pibergiim/2
- Trujillo, C.M., Anderson, T.R., & Pelaez, N.J. (2014). A tetrahedral version of the MACH model for explaining biological mechanisms. *PIBERG Instructional Innovation Materials*. http://docs.lib.purdue.edu/pibergiim/1

INVITED PRESENTATIONS

- Trujillo, C. (2014). How SFES training prepares one to teach undergraduate students to explain cellular mechanisms like a practicing biologist. On the Origin of Science Faculty with Education Specialties (SFES): Perspectives on Their Roles and Tensions. Experimental Biology. April 26-30. San Diego, CA, USA.

ABSTRACTS

- Trujillo, C., Anderson, T. R., & Pelaez, N. (2014). The MACH model for explaining molecular mechanisms: themes across multiple disciplines. Experimental Biology. April 26-30, 2014. San Diego, CA, USA.
- Trujillo, C., Anderson, T. R., & Pelaez, N. (2014). A model of biology experts' mechanistic explanations: themes across multiple disciplines. National Association for Research of Science Teaching. March 30-April 2. Pittsburg, PA, USA.
- Trujillo, C., Alaniz, J., Anderson, T. R., & Pelaez, N. (2014). Research to practice: Using the MACH model to improve student learning in the life sciences. Annual Graduate Student Educational Research Symposium. March 14. West Lafayette, IN, USA.
- Trujillo, C. & Pelaez, N. (2013). An expert-like explanatory framework for learning cellular and molecular mechanisms. Experimental Biology. April 19-22. Boston, MA, USA.
- Trujillo, C. & Pelaez, N. (2013). An expert-like explanatory framework for learning cellular and molecular mechanisms. Annual Graduate Student Educational Research Symposium. March 19. West Lafayette, IN, USA.
- Hiatt, A., Perez, K.E., Davis, G. K., Terry, M., Trujillo, C., French, D. P., & Price, R. M. (2012). Evo-devo: target concepts and students' challenges. National Association of Biology Teachers, October 31 - November 3. Dallas, TX, USA.
- Trujillo, C. & Walker, W. (2012). Nature of science and professional development of elementary educators. National Outreach Scholarship Conference. September 30 - October 3. Tuscaloosa, AL, USA.
- Trujillo, C. & Pelaez, N. (2012). The role of mechanistic explanations in cellular and molecular biology according to experts and novices. Society for the Advancement of Biology Education Research (SABER) National Meeting. July 12-15. Minneapolis, MN, USA.

- Perez, K. E., Price, R. M., Andrews, T. M., Abraham, J. K., Davis, A. D., Hiatt, A., McElhinny, T. L., Mead, L. S., Smith, M. U., Terry, M., Thanukos, A., Trujillo, C., & Walker, R. M. (2012). Common conceptual difficulties biology undergraduates share about distinct evolutionary content areas. SABER National Meeting. July 12-15. Minneapolis, MN, USA.
- Haitt, A., Perez, K. E., Davis, G. K., Trujillo, C., Terry, M., French, D.P., & Price, R. M. (2012). Evaluating students misconceptions in Evo-Devo. Evo-Devo IGERT symposium. February 10-12, 2012, Portland, OR, USA.
- Trujillo, C. (2012). The nature of science from the viewpoint of a professional development team. The Department of Education's Math and Science Partnership, Regional Conference. January 30, 2012. New Orleans, LA, USA.
- Knight, J.K., Wise, S., Southard, K., Wood, W., & Trujillo, C. (2011). Development of a capstone molecular biology concept assessment (Capstone MBCA). SABER National Meeting. July 29-31, 2011. Minneapolis, MN, USA.
- Klymkowsky, M.W., Cooper, M., Bryfcynski, S., Trujillo, C., & Underwood, S. (2011). Formative conceptual (Socratic) assessment and its role in course and curricular design for general chemistry & basic molecular biology. SABER National Meeting. July 29-31. Minneapolis, MN.
- Trujillo, C. M. (2010). Use of Diagnostic Question Clusters (DQCs), questioning answer space. Investigating Students' Scientific Reasoning about Biological Experiments. November 13. West Lafayette, IN, USA.
- Trujillo, C. M., & Klymkowsky, M.W. (2010). Graphing and Socratic tutorials improve student thinking about gene networks. Society for Developmental Biology 69th Annual Meeting. August 5-9. Albuquerque, NM, USA.

WET-LABORATORY RESEARCH EXPERIENCE

Independent Project. Purdue University. 2011

Gene regulatory network of Irx7 in the vertebrate retina. Collect gene expression data and analyze morphant zebrafish. PI: Leung

Laboratory Assistant. University of Colorado at Boulder. 2008 – 2009
Adult Stem Cell Research Team. Genotype transgenic mice for Muscular Dystrophy model. Assist research on muscle regeneration. PI: Olwin

AWARDS & HONORS

- Society for the Advancement of Chicanos and Native Americans in Science (SACNAS) Outstanding Governance Chapter Award 2014
- Graduate Teaching Assistant Honor Roll for the Department of Biological Sciences 2014
- Best Poster Award for 7th Annual Graduate Student Educational Research Symposium 2014
- One of 5 Students Who Move the World Forward, Purdue University 2014
- Graduate/Postdoctoral Travel Award for American Society for Biochemistry and Molecular Biology 2014
- Travel Award for SABER conference (NSF award to SABER) 2012
- SACNAS Chapter award - Outstanding Leadership on Campus Award 2012
- Dr. P.T. Gilham Graduate Scholarship Fund for interdisciplinary research 2010 – 2011
- Tutor of the Year by Academic Support Assistance Program (ASAP) 2008 – 2009
- Norlin Scholar 2005 – 2008

TEACHING EXPERIENCE

Teaching Assistant. Purdue University. 2014
Freshmen Biology Seminar. Prepare students for academic achievement in the biological sciences program. Teach as an independent instructor. Supervise teaching interns.

Teaching Assistant Purdue University. 2014
Cell Biology Laboratory. Teach students laboratory methods for studying proteins and nucleic acids in cellular systems. Prepare solutions and troubleshoot laboratory exercises.

Teaching Assistant. Purdue University. 2014
Development, Structure and Function of Organisms. Manage and train nine peer leaders to use an online environment to hold problem-solving sessions. Facilitate small group discussions with students via Adobe Connect.

Teaching Assistant. Purdue University. 2010 – 2013
Biology for Elementary Teachers (Three semesters). Teach process and skill-oriented laboratory sections. Create and score formative and summative assessments. Support students through one-on-one meetings.

Cyber Peer Leader. Purdue University. 2011
Teaching Evolution: Next-Generational Learning Challenges. Facilitate synchronous online classroom through peer lead discussions.

Learning Assistant. University of Colorado. 2011
Developmental Biology. Facilitate peer discussions. Guide problem-solving.

Tutor for Academic Support Assistance Program (ASAP). University of Colorado. 2007 - 2010
Guide individual students to succeed in biology and physics. Facilitate group work. Create tutorials and resources.

PROFESSIONAL DEVELOPMENT

Cyber Peer Lead Team Learning (cPLTL). Indiana University Purdue University of Indianapolis. 2011
Trained in online synchronous learning in a distance-learning environment using Adobe Connect.

CU Science Education Initiative. University of Colorado at Boulder. 2009 – 2010
Trained as Science Teaching Fellows (Post-doctoral level). Assessment development, classroom transformation, expert-novice framework, educational statistics, and research methodologies.

AFFILIATIONS/MEMBERSHIPS

Co-founder of Purdue International Biology Education Research Group (PIBERG) 2011 – 2015

Member of Visualization in Biochemistry Education (VIBE) Research Group 2012 – 2015

Member of American Society for Biochemistry and Molecular Biology (ASBMB) 2014

Member of National Association for Research in Science Teaching (NARST) 2014

Co-founder of Discipline-based Education Research for Graduate Students (DBER-GS) at Purdue University 2012 – 2014

Charter member of Society for the Advancement of Biology Education Research (SABER) 2011 -2015

Elected board member of Purdue Chapter Society for Advancement of Chicanos and Native Americans in Science (SACNAS). Community Service Coordinator & Vice President. 2011 - 2014

SERVICE

Assessment of Competence in Experimental Design in Biology (ACED-Bio) Network Retreat. Volunteer. May 18-23, 2014, Lafayette, IN, USA.

Society for the Advancement of Biology Education Research. Reviewer. July 17-20, 2014, Minneapolis, MN, USA.

National Association for Research of Science Teaching. Reviewer. March 30-April 2, 2014. Pittsburg, PA, USA.

Biology Directors Consortium Conference at National Association of Biology Teachers. Invited participant. November 23, 2013, Atlanta, GA, USA.

Best Practices in Undergraduate Biology Education: Midwest Regional Exchange. Invited participant. November 1 - 3, 2013, West Lafayette, IN, USA.

National Evolution Synthesis Center working group EvoCI Toolkit: Concept Inventories to Assess Conceptual Understanding of Evolution. Invited member. 2011 - 2013, Durham, NC, USA.

Assessment of Students - Reasoning with Core Concepts and Visualizations in Biochemistry. Invited participant. November 3, 2012, West Lafayette, IN, USA.